A Conversation about Rivers and Dams …

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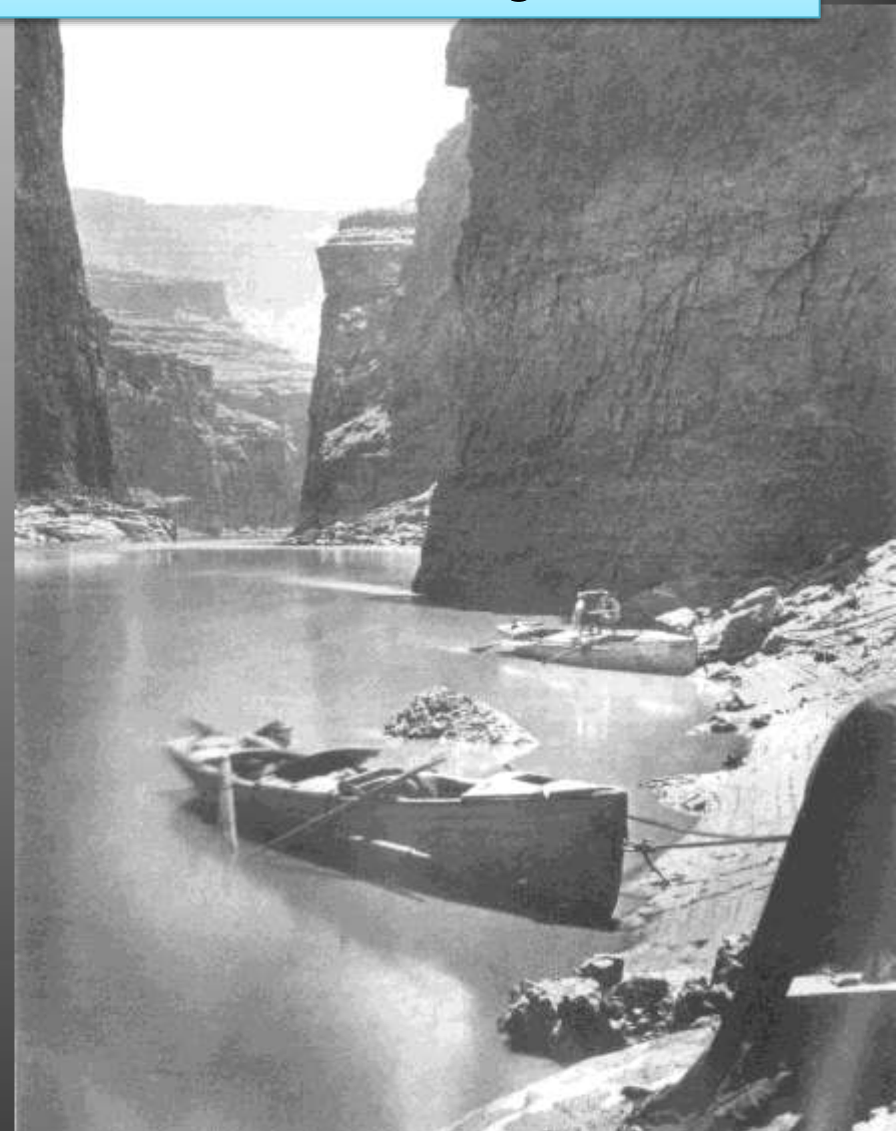
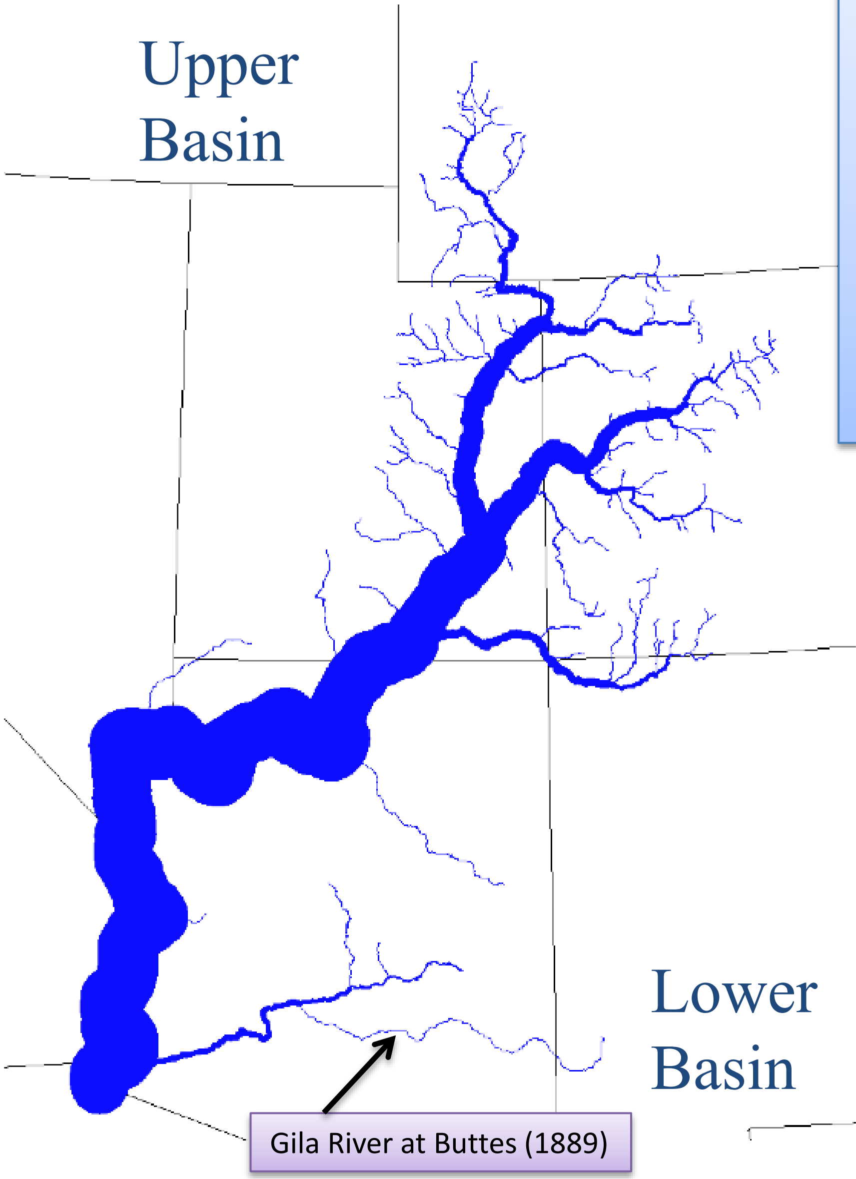
First scientific observations in Grand Canyon made by Powell (1875, 1895). Early photographs are an essential benchmark for environmental monitoring.

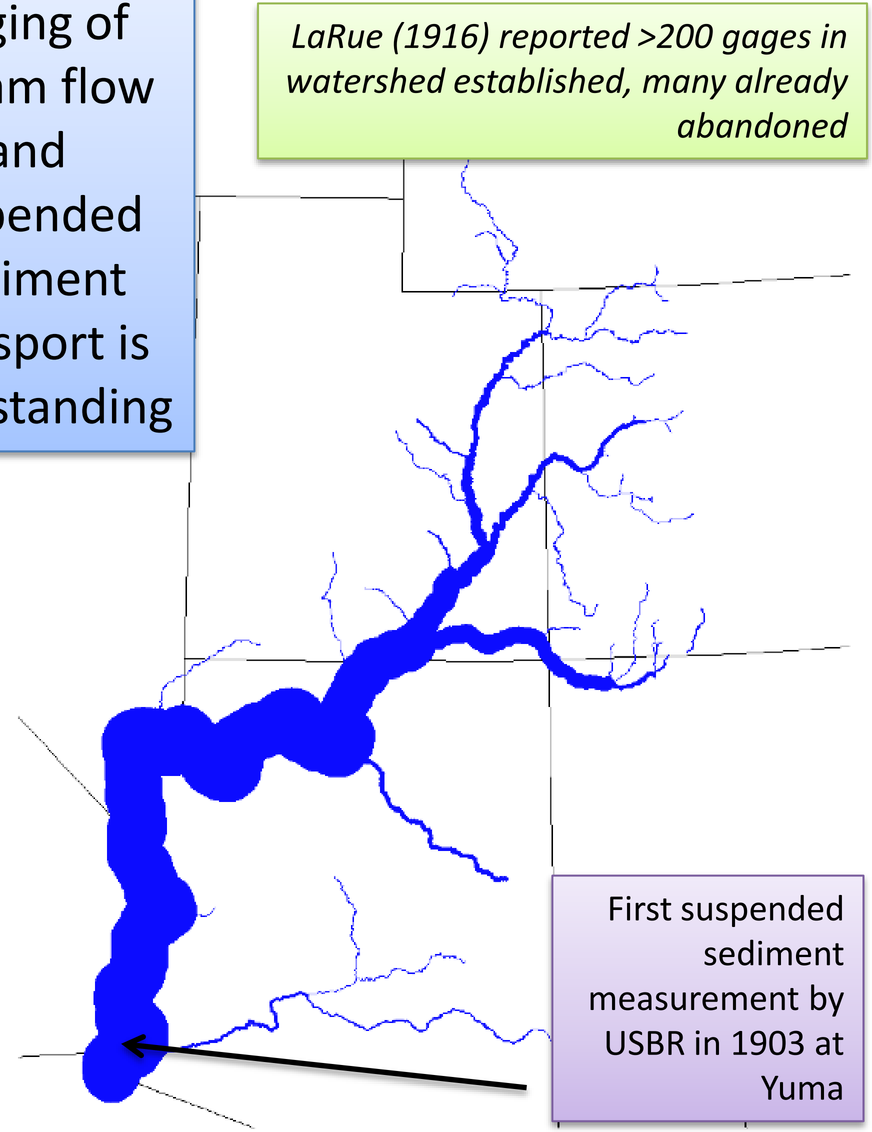
Badger Creek Rapids, 1920s



Marble Canyon, 1872

Gaging of stream flow and suspended sediment transport is long-standing





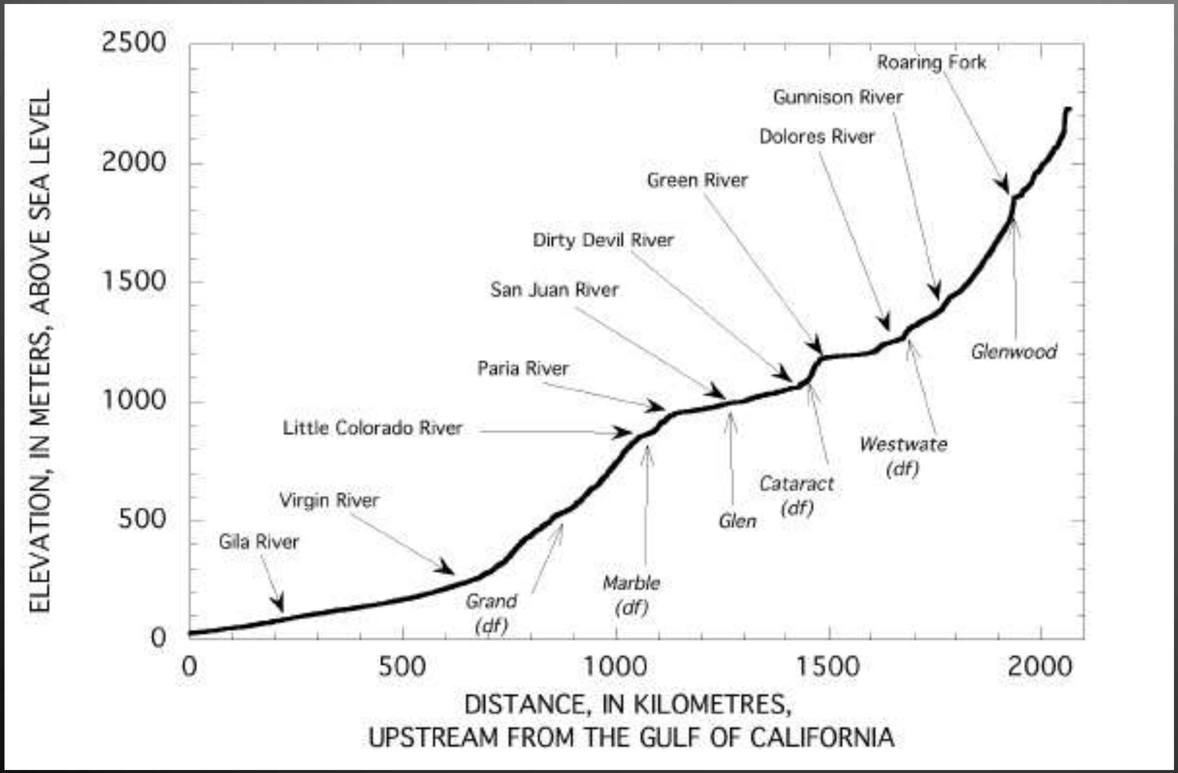
water

sediment

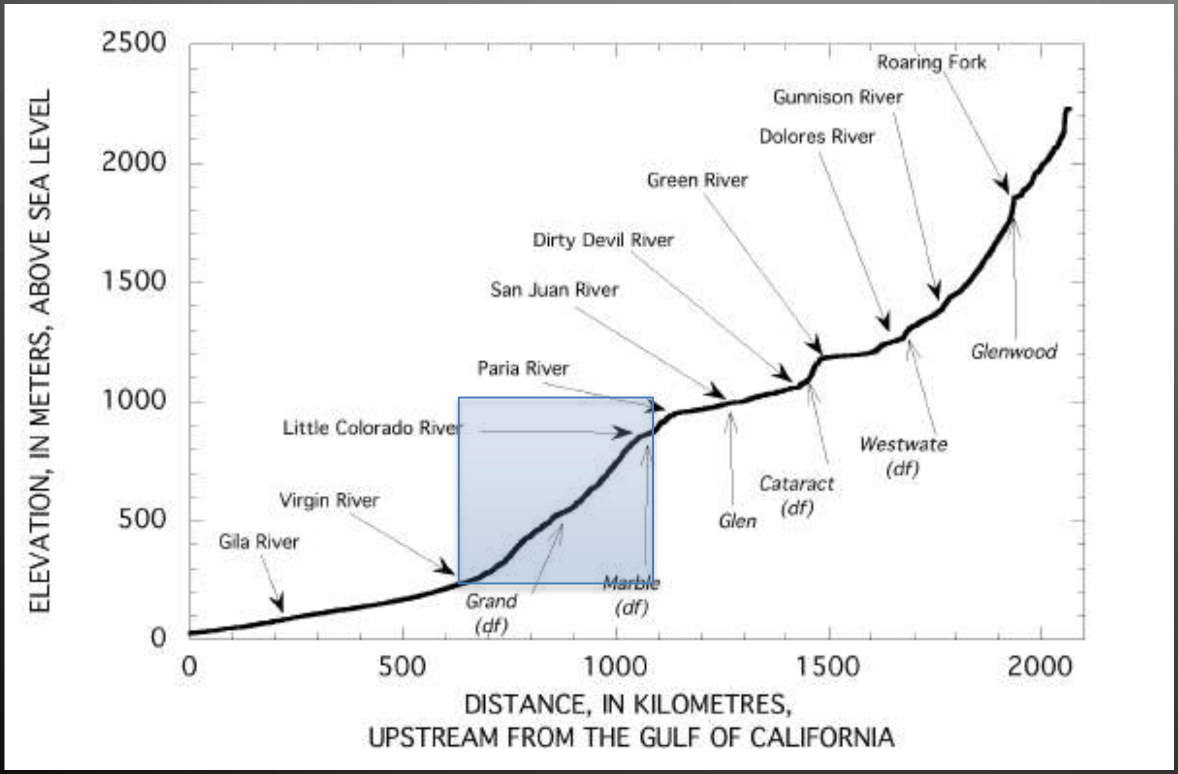
54% of total runoff at Lees Ferry in already in the channels of the upper 15% of the basin

(data adapted from Iorns et al., 1965)

Early measurements of the physical structure of the river date to the 1920s



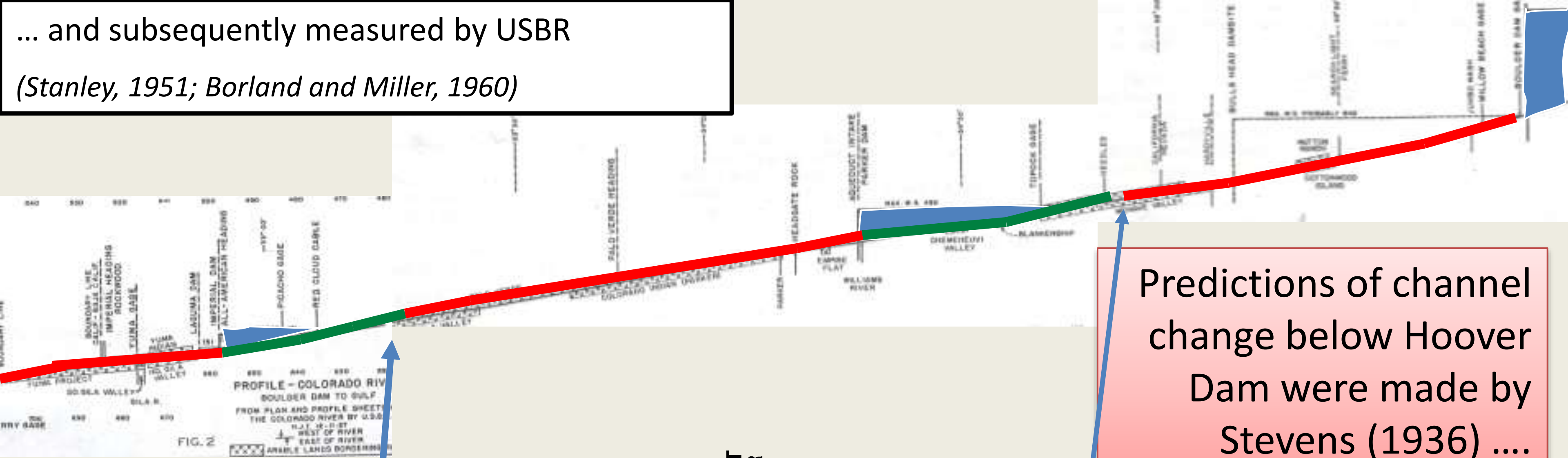
The Grand Canyon segment was the last part of the river system surveyed.



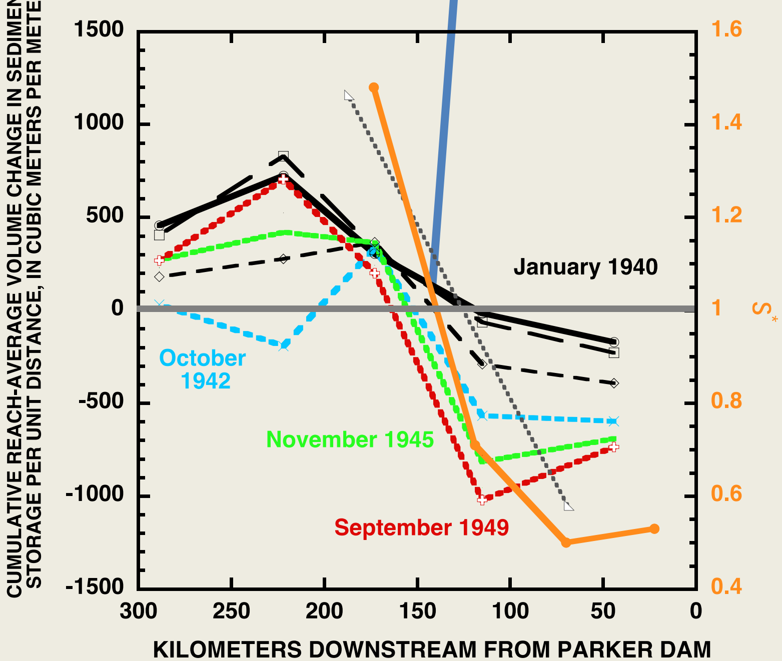
Birdseye (1924)

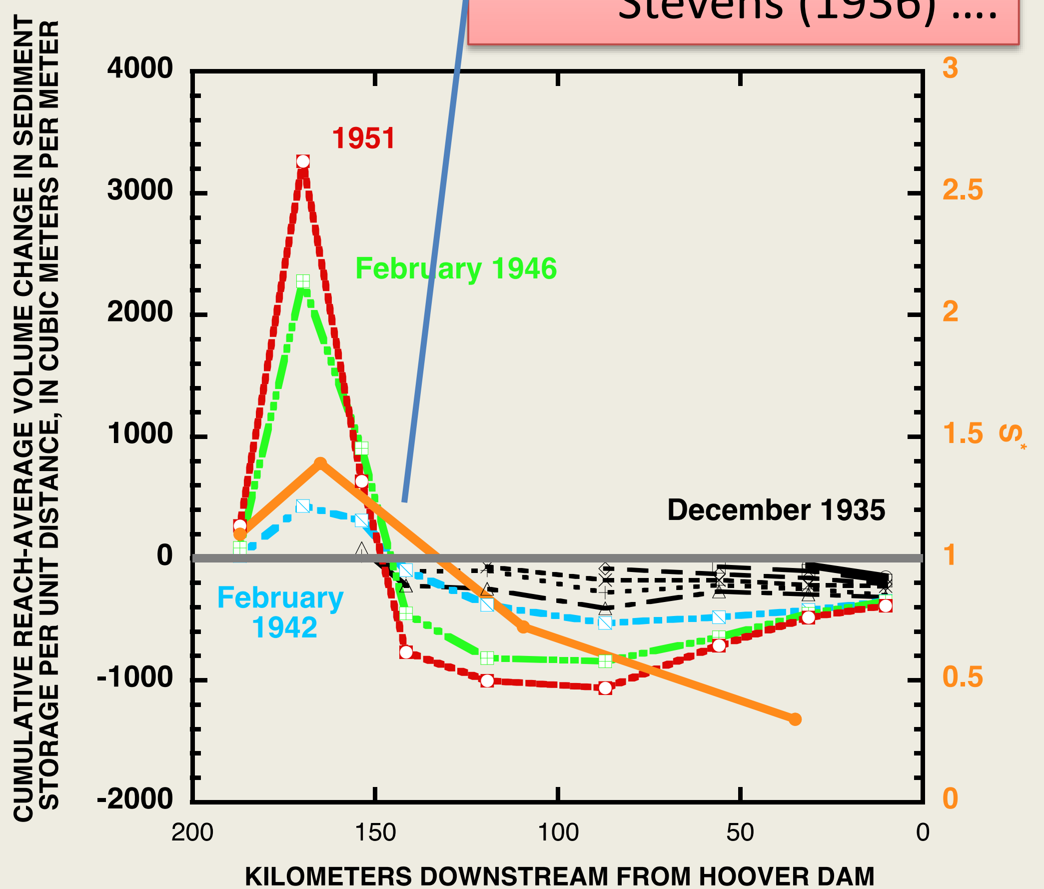
… and subsequently measured by USBR

(Stanley, 1951; Borland and Miller, 1960)

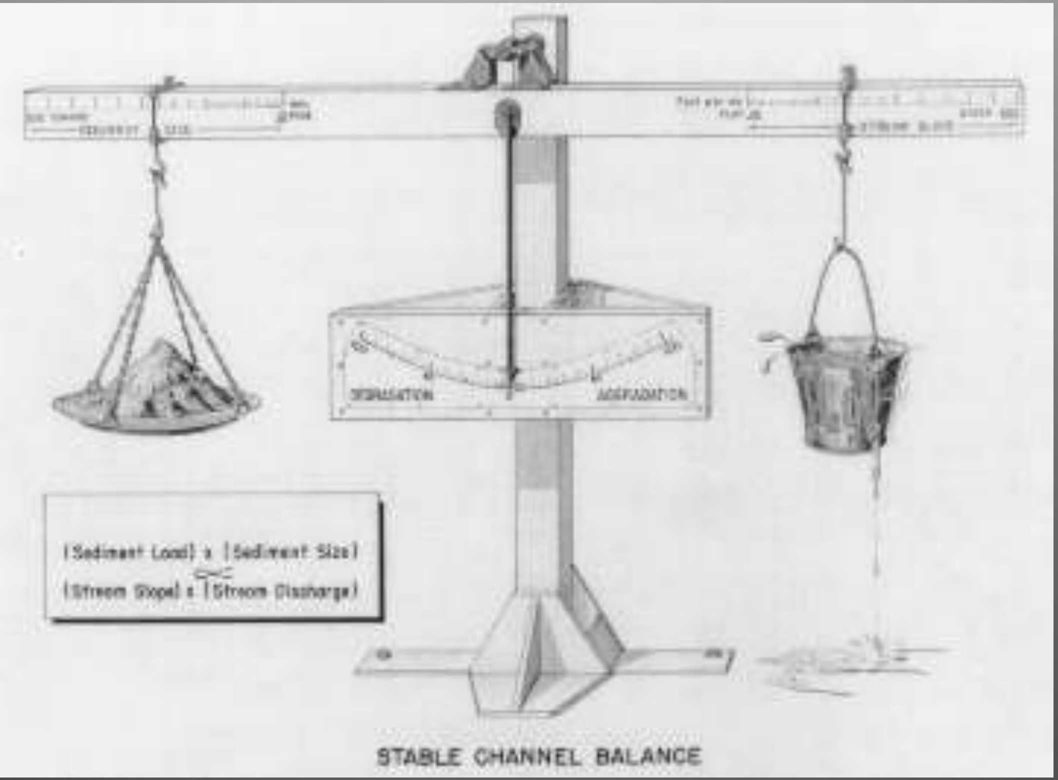


Predictions of channel change below Hoover Dam were made by Stevens (1936) ….





Downstream channel change results from perturbing the balance between the capacity of a river to transport sediment and the amount of sediment supplied to the channel



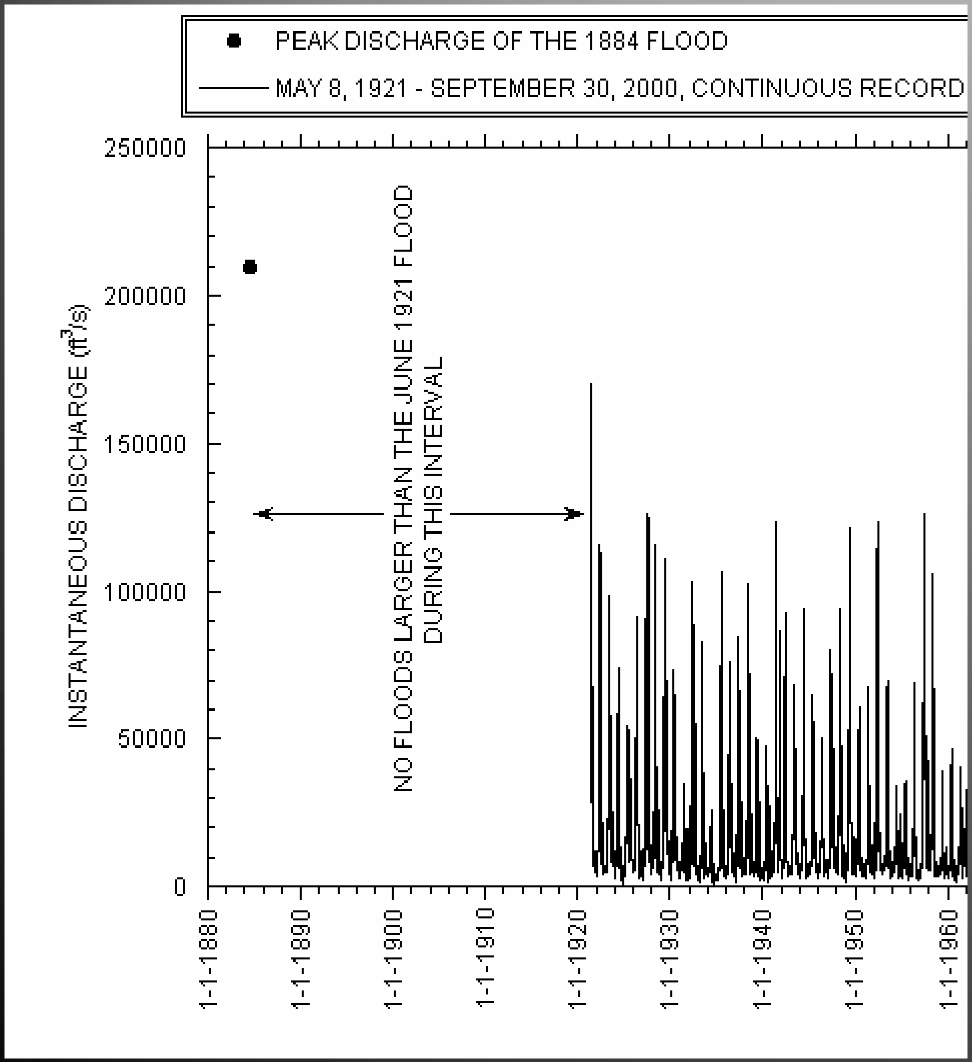
Factors that induce degradation below dams:

- Reduced sediment supply
- Fining of sediment supply
- Increased sediment transport capacity from elevated baseflows

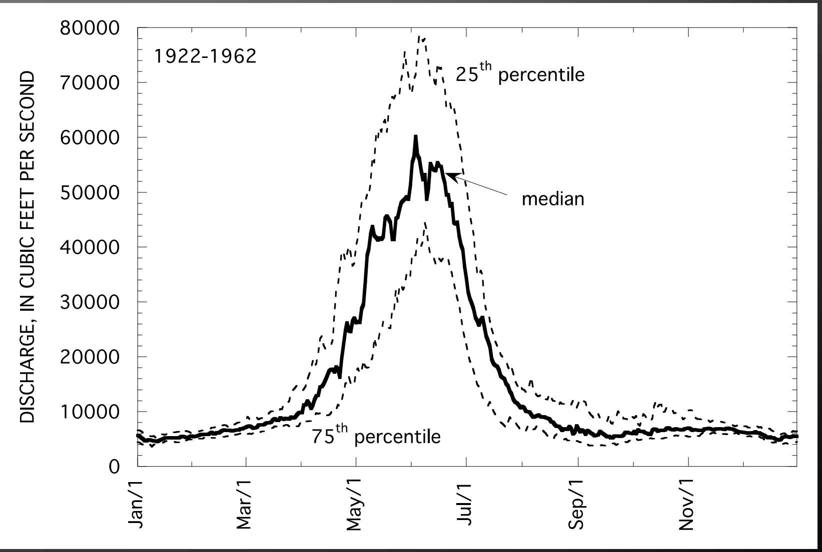
Factors that induce aggradation below dams:

- Reduced sediment transport capacity from reduced floods

The stream flow that passes through Grand Canyon comes from the Rocky Mountains.

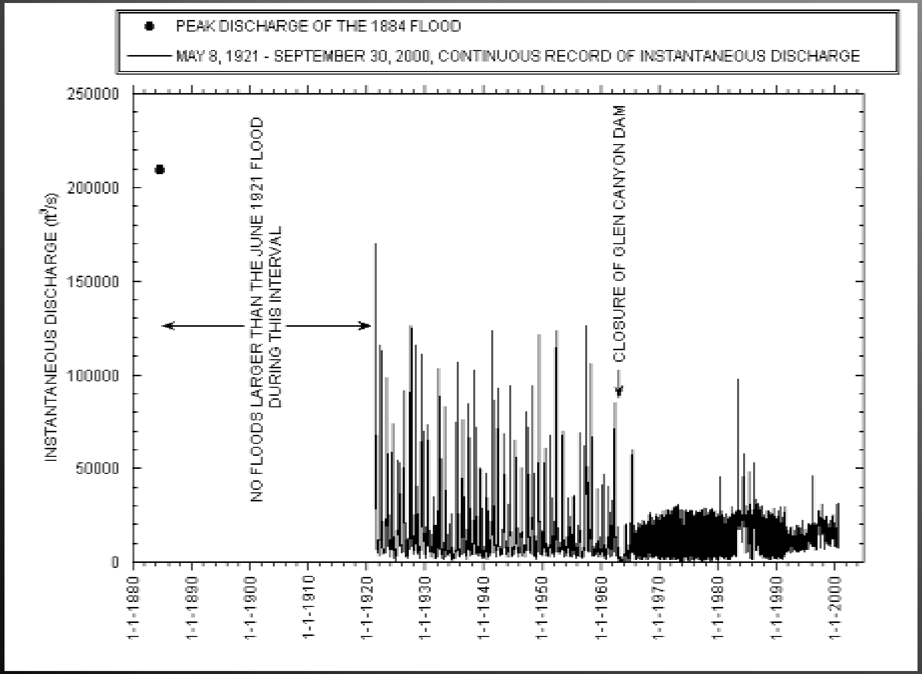


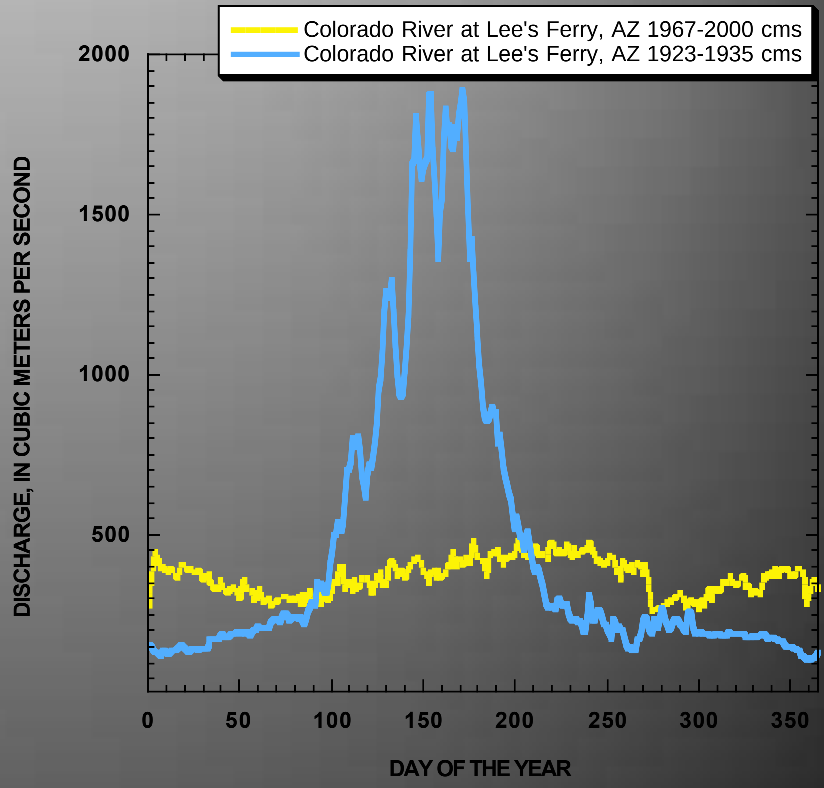
- Pre-dam (1921-1963) flow regime in Grand Canyon
  - **7,980** ft^3/s (50% of the time)
  - Flow greatest in **June** (51,200 ft^3/s 50% of the time)
  - Flow lowest in **January** (5,140 ft^3/s 50% of the time)
  - **50,000** ft^3/s flood occurred every year, on average
  - **125,000** ft^3/s flood occurred every 8 years, on average



Topping et al. (2003)

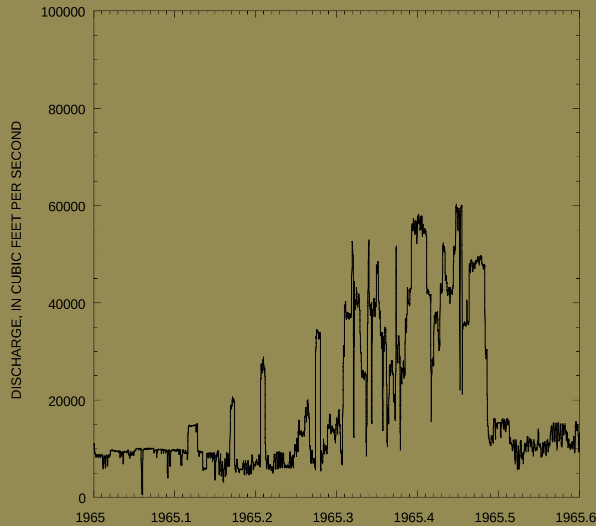
- Post-dam flow regime (1963-2000)
  - **12,600** ft^3/s (50% of the time)
  - Flow greatest in **August** (16,400 ft^3/s 50% of the time)
  - Flow lowest **in October** (10,200 ft^3/s 50% of the time)
  - **30,000** ft^3/s flood occurs every year, on average
  - **50,000** ft^3/s flood occurs every 8 years, on average

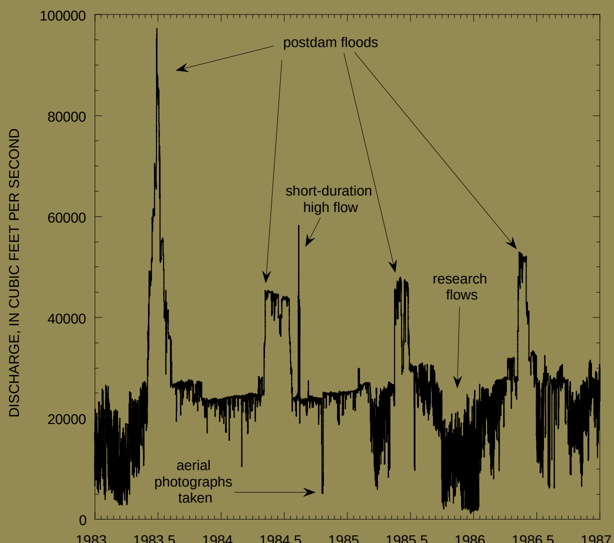




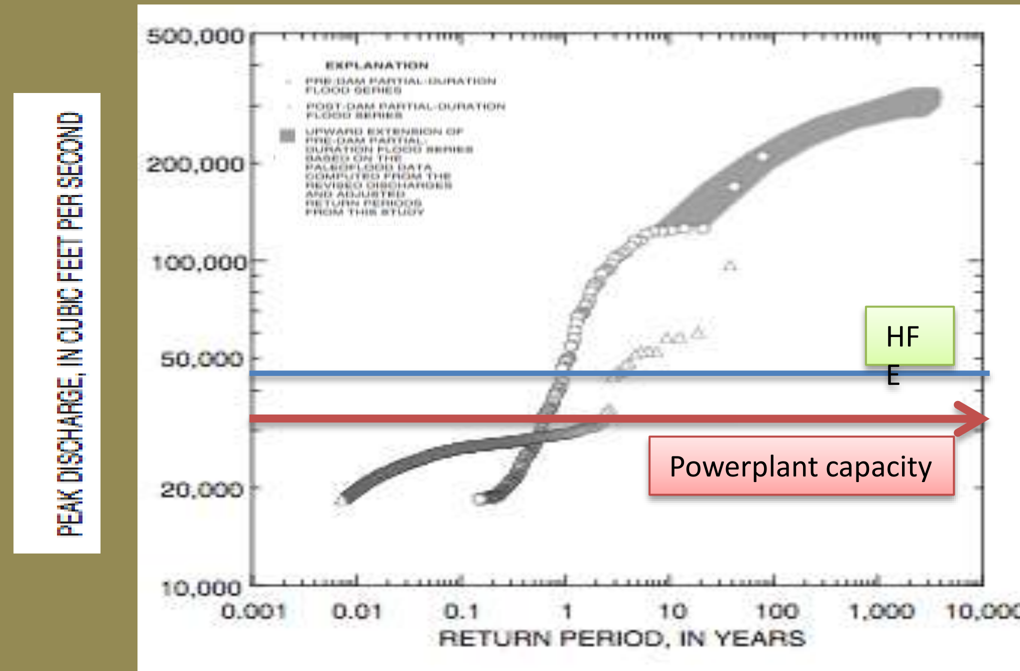
Topping et al. (2003)

(Topping et al., 2003)



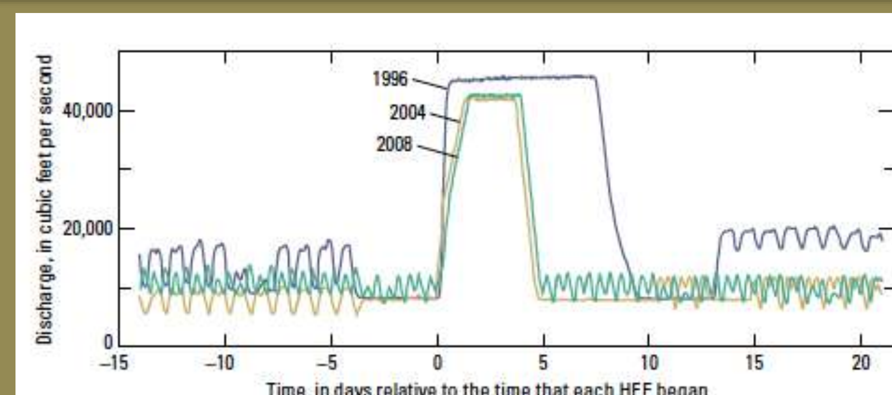


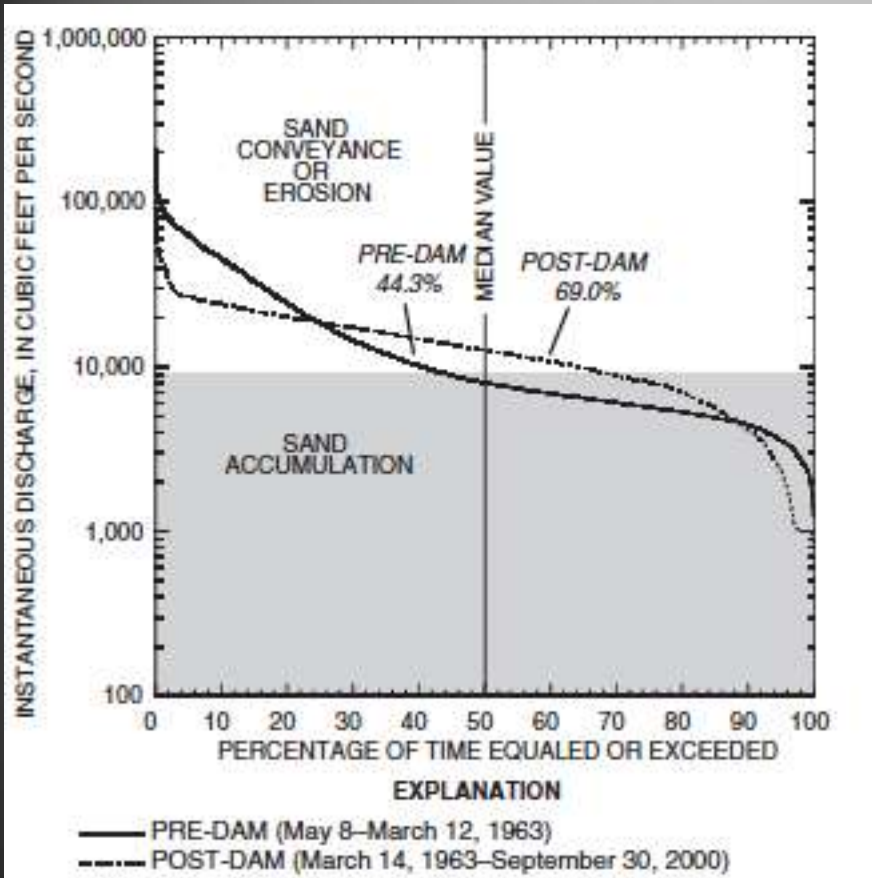
Post-dam floods occurred in 1965, 1983, 1984, 1985, 1986



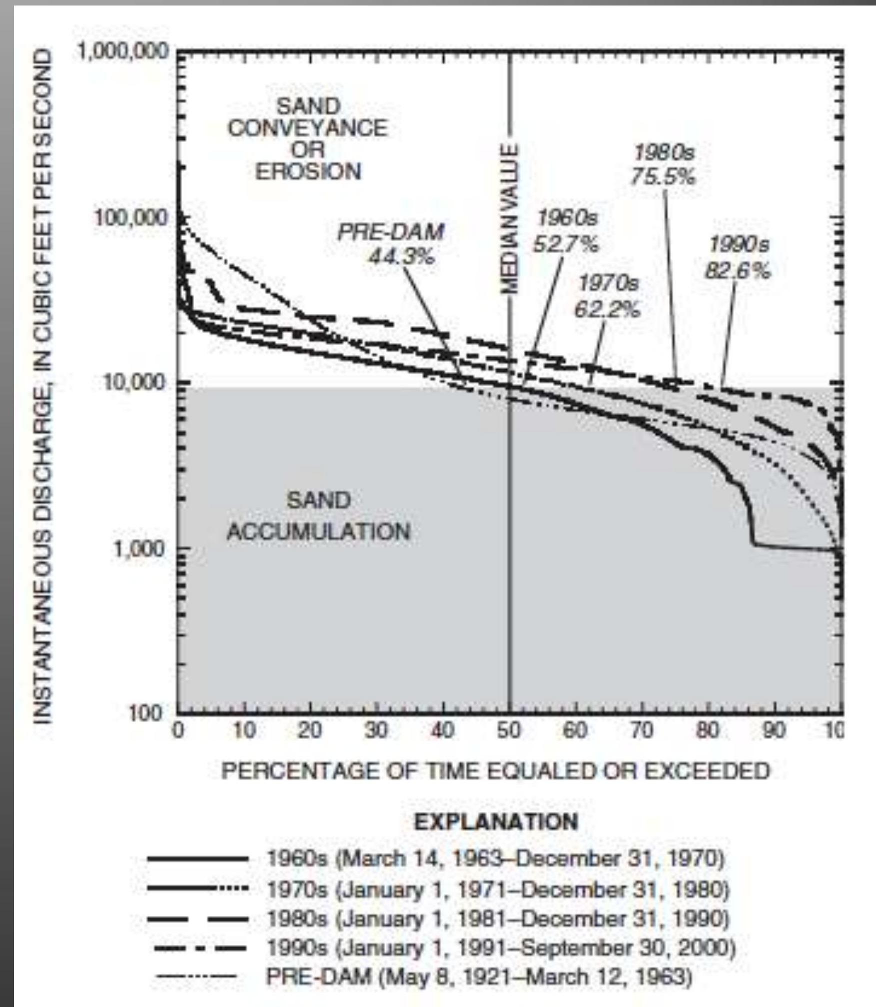
(Topping et al., 2003)

Short duration high flows occurred in 1965, 1980, 1996, 2004, and 2008

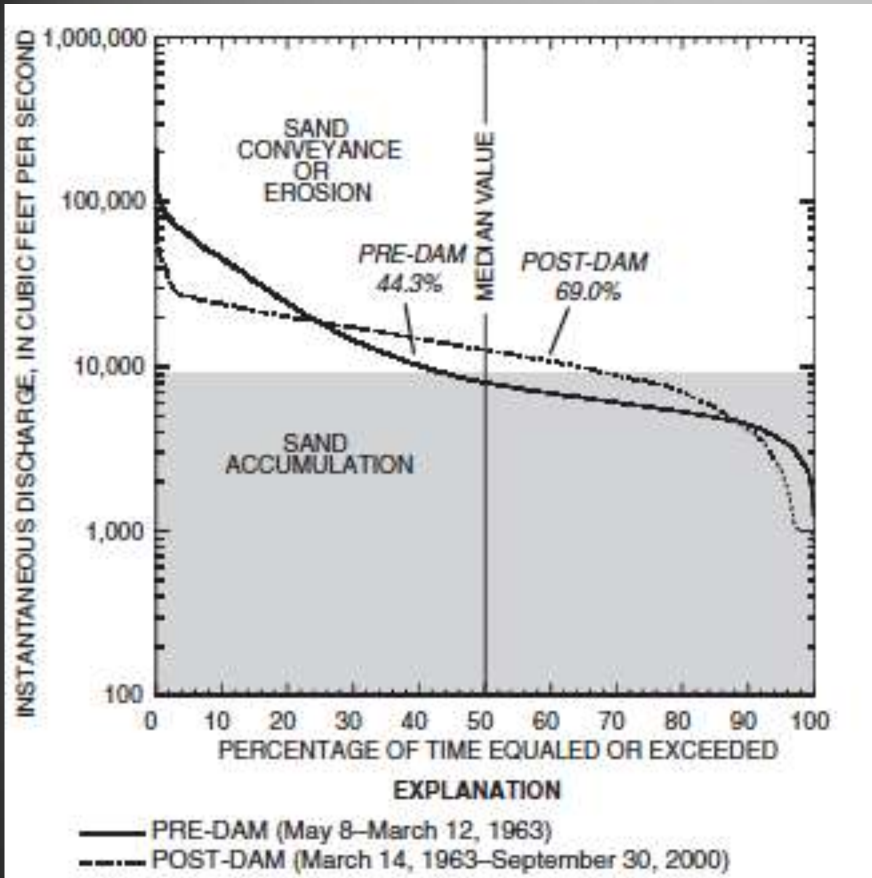




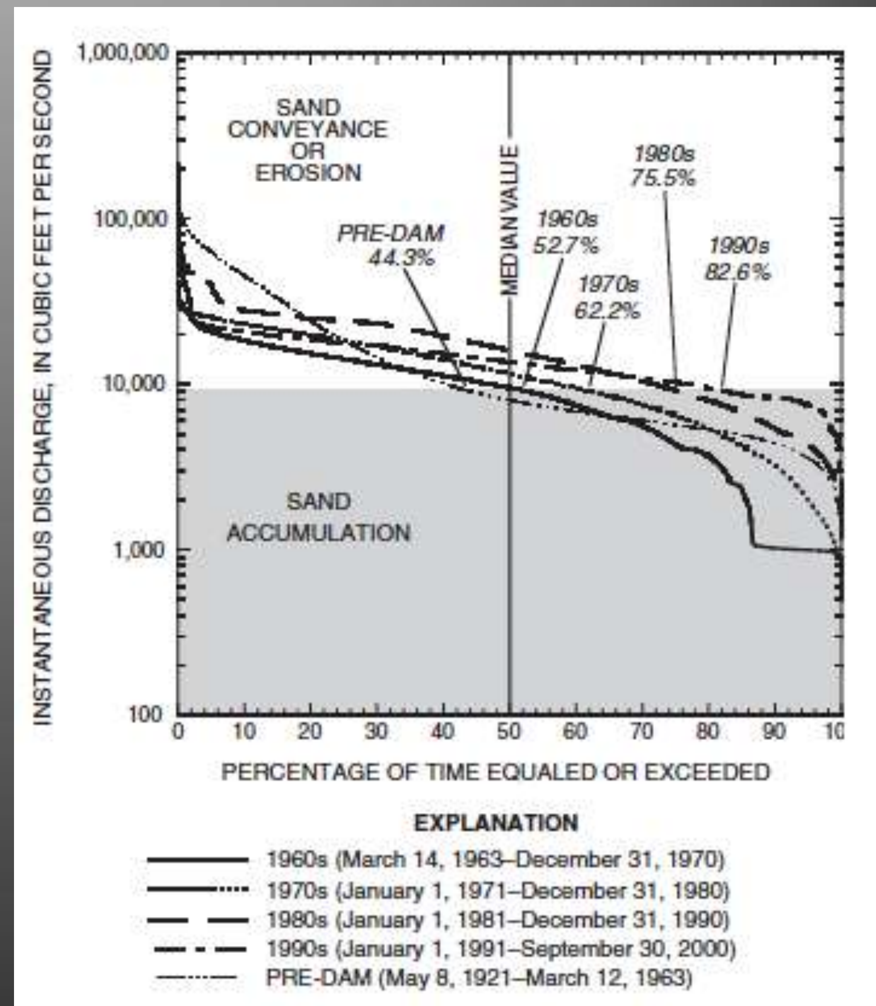
Elevated base flows have a significant impact on sand accumulation in Grand Canyon



(Topping et al., 2003)



Elevated base flows have a significant impact on sand accumulation in Grand Canyon

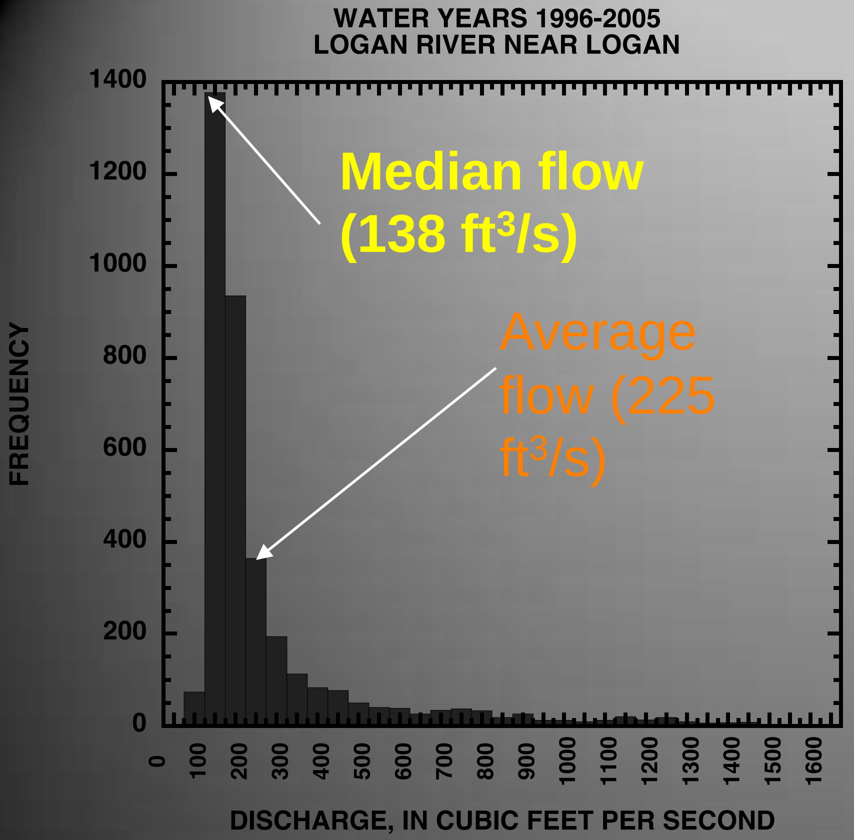


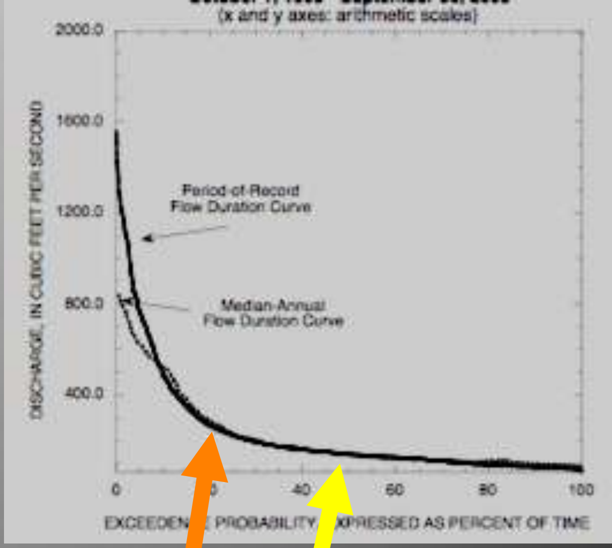
Flow duration curve: a concise picture of the temporal variability of stream flow [but do not reflect seasonality or autocorrelation]

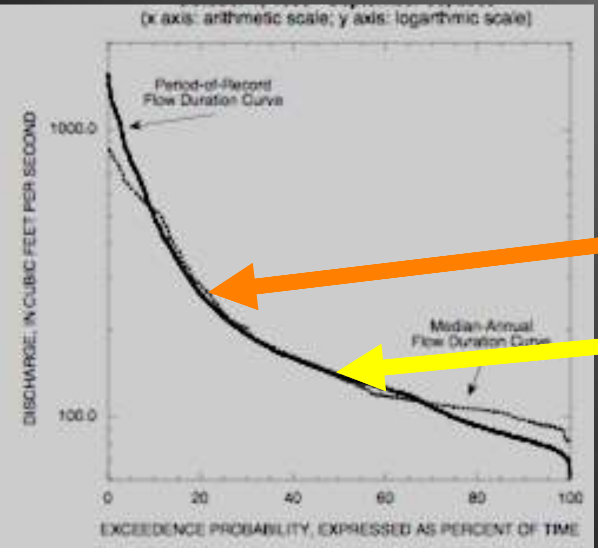
A cumulative frequency curve showing the fraction of time flows exceed a specific value

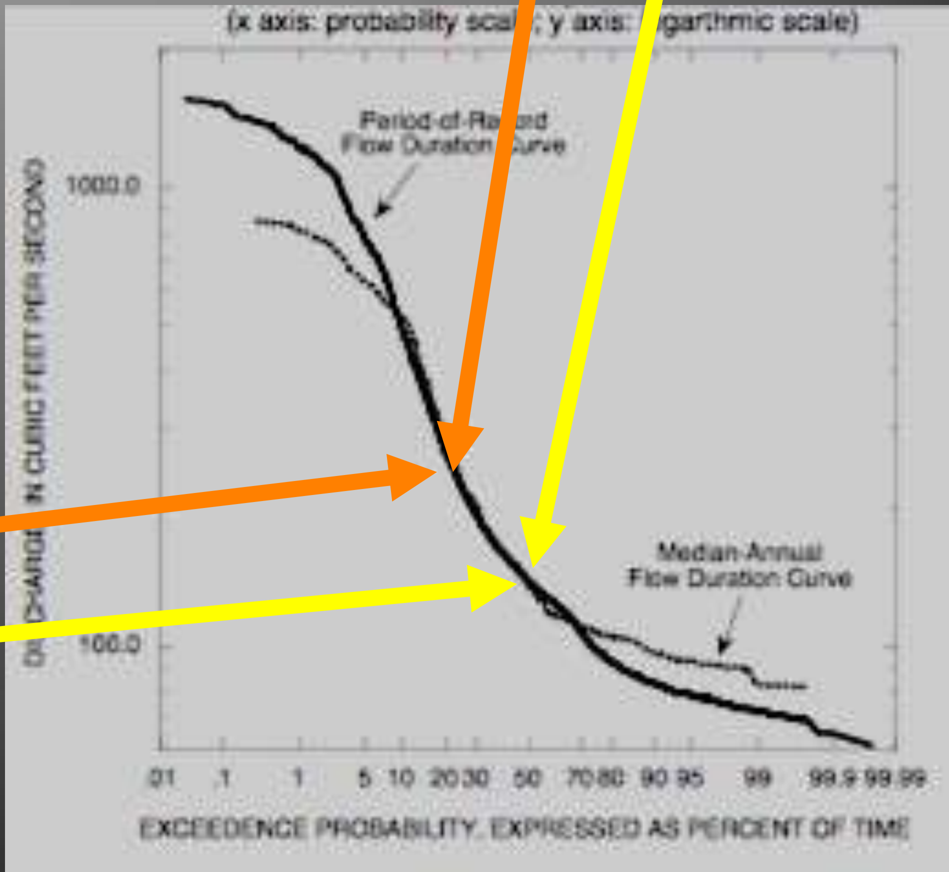
(Topping et al., 2003)

Ways to plot flow duration curves



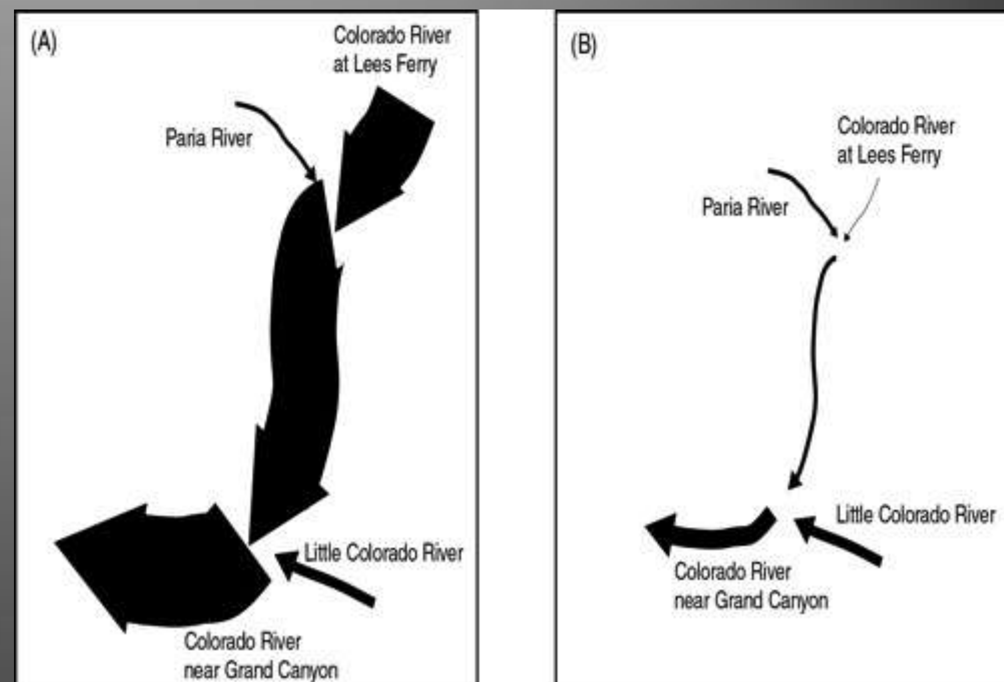






It is essential to understand the natural sediment supply

Annual average sediment load downstream from Glen Canyon Dam



adapted from Topping (2000)

General agreement in the fine sediment supply rate from Paria (1.4-1.9 x 10^6 tons) and Little Colorado River (3.3-3.4 x 10^6 tons)

Disagreement about sediment contribution from lesser tributaries:

4.4 x 10^6 tons *(Howard and Dolan, 1981)*

0.7 x 10^6 tons *(Randle and Pemberton, 1987)*

Longstanding research themes in Grand Canyon research

Is the Colorado River in Grand Canyon evacuating or accumulating sediment?

What controls the large-scale organization of the Colorado River and its valley?

What is the small scale organization of the river?

What are the hydraulics of flow in fan-eddy complexes and how do they change with discharge? How do these changes affect resources?

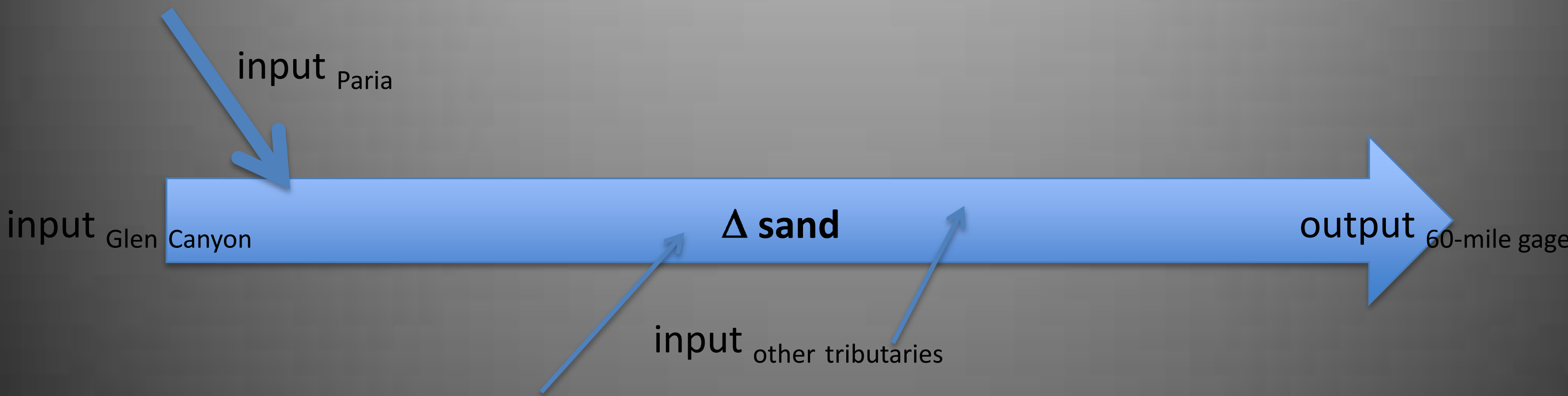
How does the channel bed adjust at annual and decadal timescales?

How do eddy sandbars adjust at annual and decadal timescales?

What have been the short and long-term changes in eddy sandbars?

What is a sediment mass balance?

Inputs – outputs = change in storage



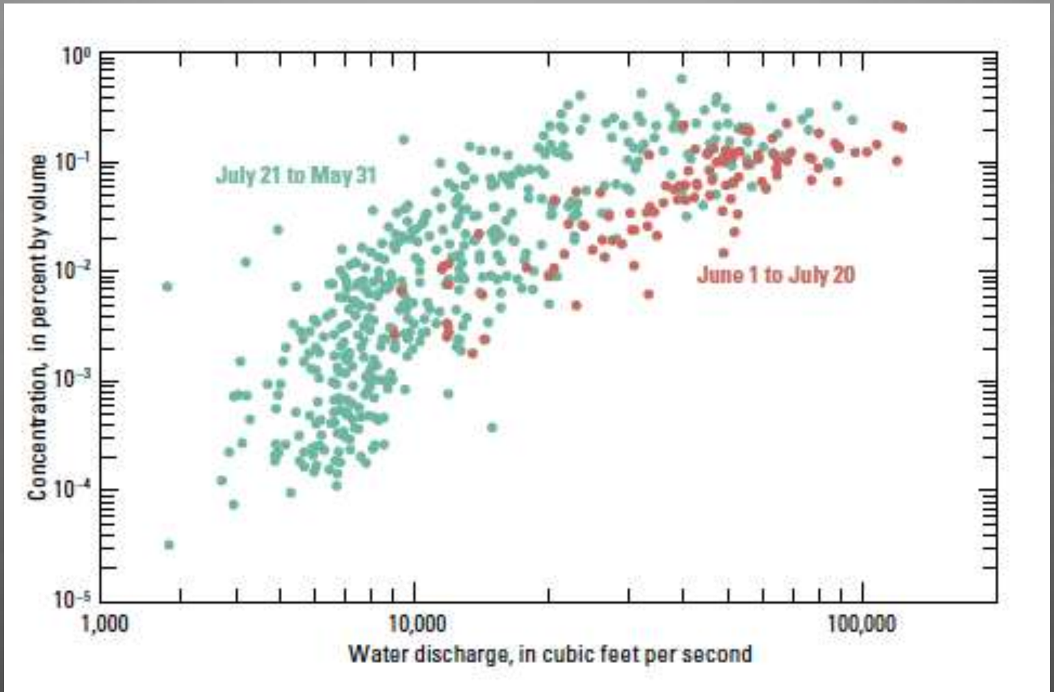
A sediment mass balance for Marble Canyon …

$$\text{input}_{\text{Glen Canyon}} + \text{input}_{\text{Paria}} + \text{input}_{\text{other tributaries}} - \text{output}_{\text{60-mile gage}} = \Delta\ \text{sand}_{\text{bed}} + \Delta\ \text{sand}_{\text{eddies}} + \Delta\ \text{sand}_{\text{channel margins}}$$

Inputs and outputs = f (water discharge, characteristics of the sediment available to be transported)

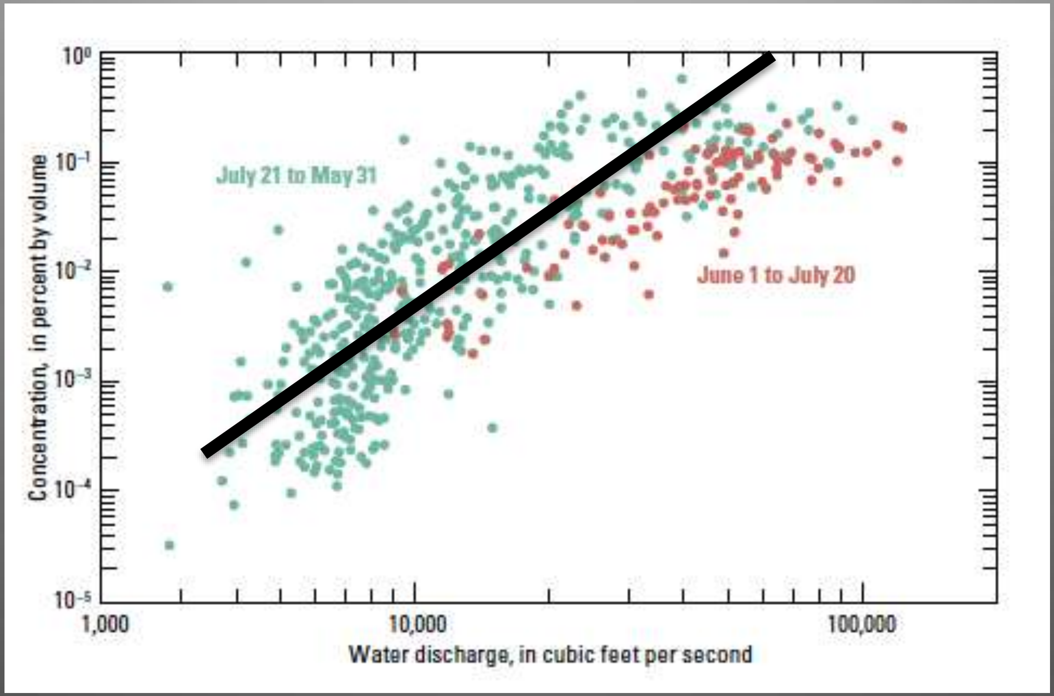
Δ sand is based on measurements of the places where sand collects

Understanding import and export of fine sediment

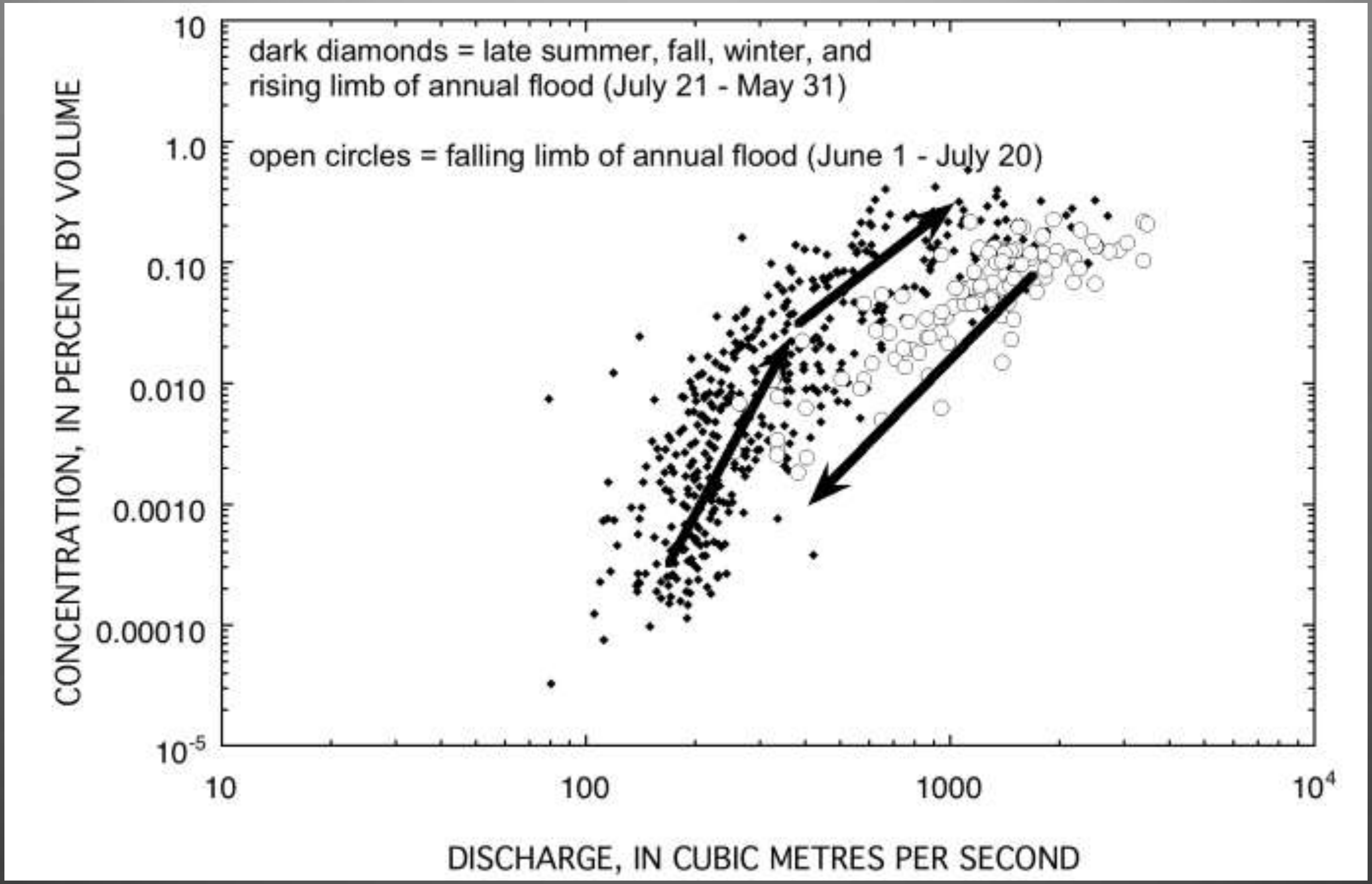


The relation between discharge and sediment transport has wide scatter

One strategy is to assume the scatter in the relation is random and fit one relation to the data



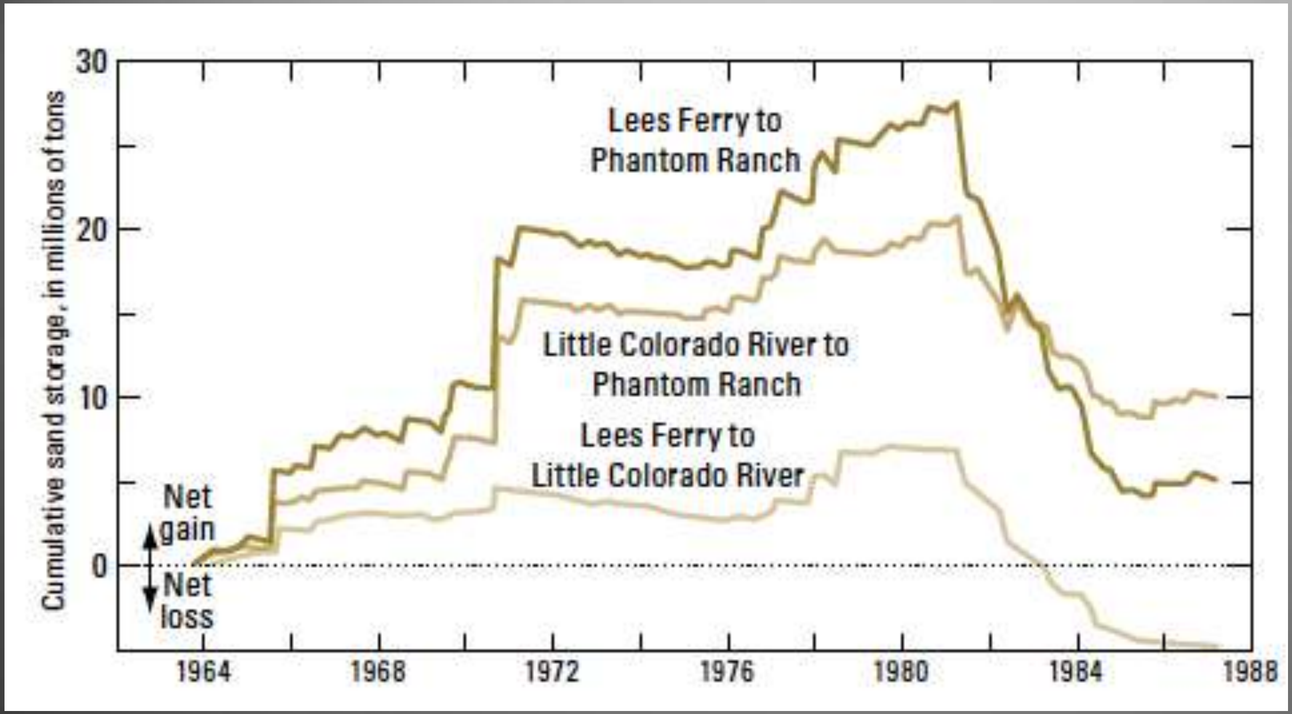
But there is a systematic pattern to these data …



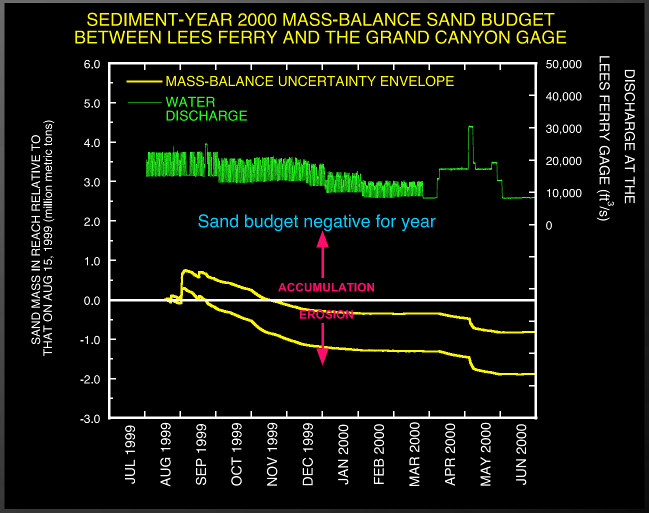
River scientists have debated the significance of these patterns for > 50 years

Colby (1964)

The old view of sediment mass balance



modern view



Failure to account for hysteresis in sediment transport relations led to the wrong conclusion about the sediment mass balance to the post-dam river.

The 1995 EIS argued that the post-dam river had been accumulating sediment when we now know that the river was losing sediment.

What is the size of sediment on the bed and in eddies?

These grain sizes affect how much sediment is imported and exported by the Colorado River

New technologies have been developed

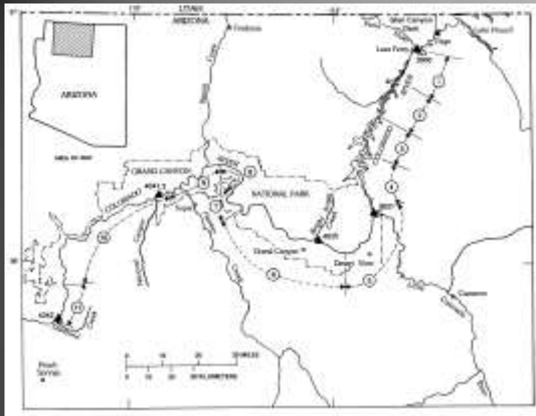
Camera with macro lens and light ring in waterproof housing.

Rubin et al., 2007, *Sedimentary Geology.*

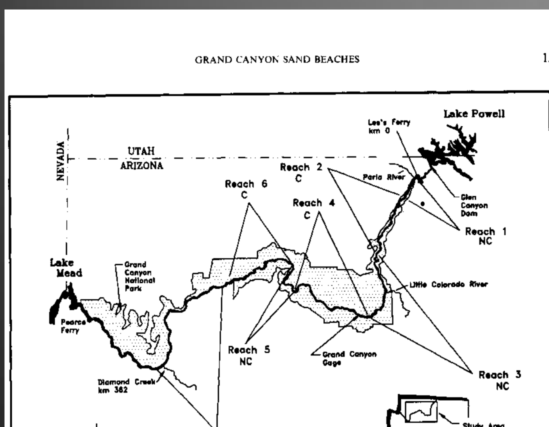

Plumbing-inspection video camera with custom optics mounted in wrecking ball.
Electric winch.
Fast! Collect >500 images per day; process as many as 10,000 overnight.

What is the large-scale architecture of the river and its valley?

How does that architecture control recreation and ecological values?



Schmidt and Graf, 1990



Kearsley et al., 1994

piscak 1980, Stephens and Shoemaker 1987, Schmidt and Graf 1990, Webb et al. 1991).

Development of water supplies has led to regulation of many of the world's rivers (Petts 1984, Gore and Petts 1989), and large dams are typically constructed in bedrock canyons. Impoundments destroy upstream riparian habitats (e.g., Woodbury 1959, Ohmart et al. 1988) and often reduce differences between baseflow and flood stage, increase daily flow fluctuations, reduce sediment transport, and alter existing downstream riparian vegetation composition (Baxter 1977, Turner and Karpiscak 1980, Howard and Dolan 1981, Nilsson 1984, Petts 1984, Williams and Wolman 1984, Ohmart et al. 1988, Johnson 1993). Hourly varying discharges produced by hydroelectric power generation create daily "tidal" fluctuations that are accentuated in narrow

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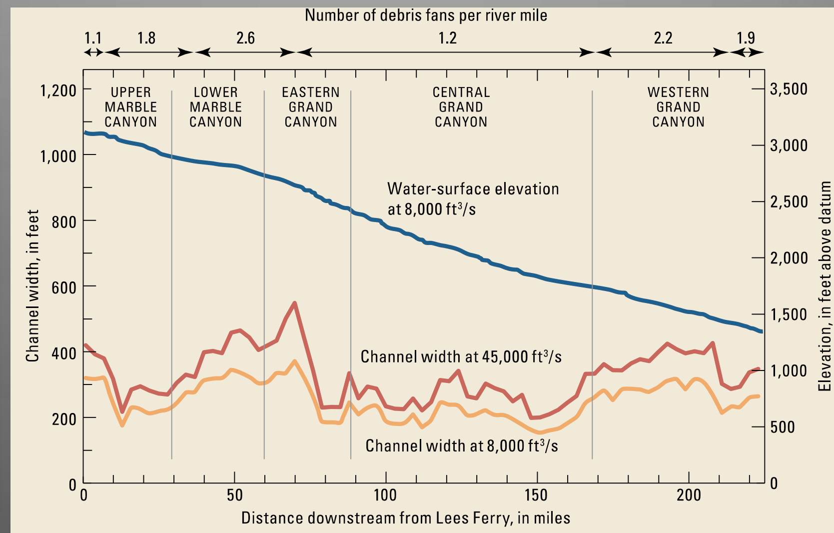
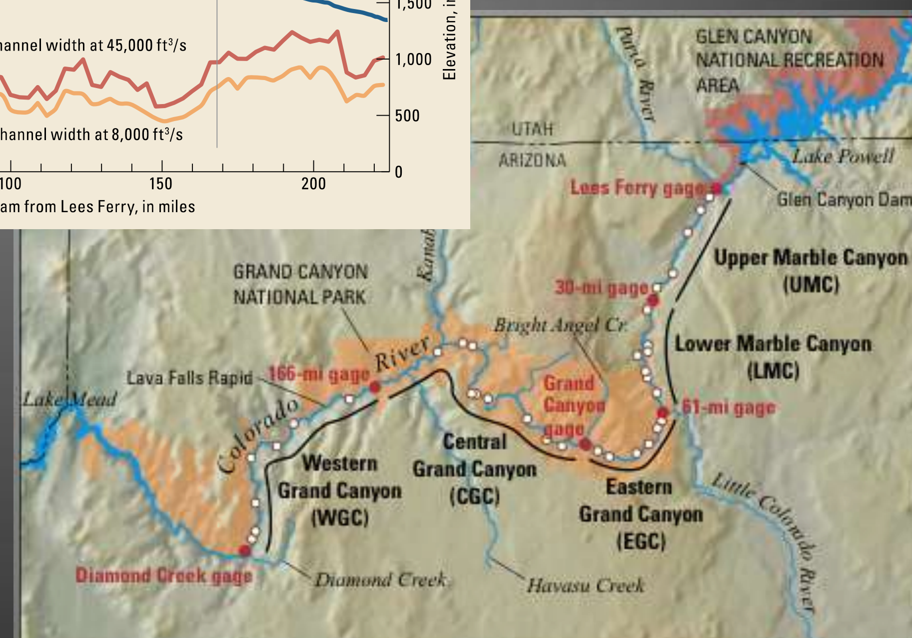
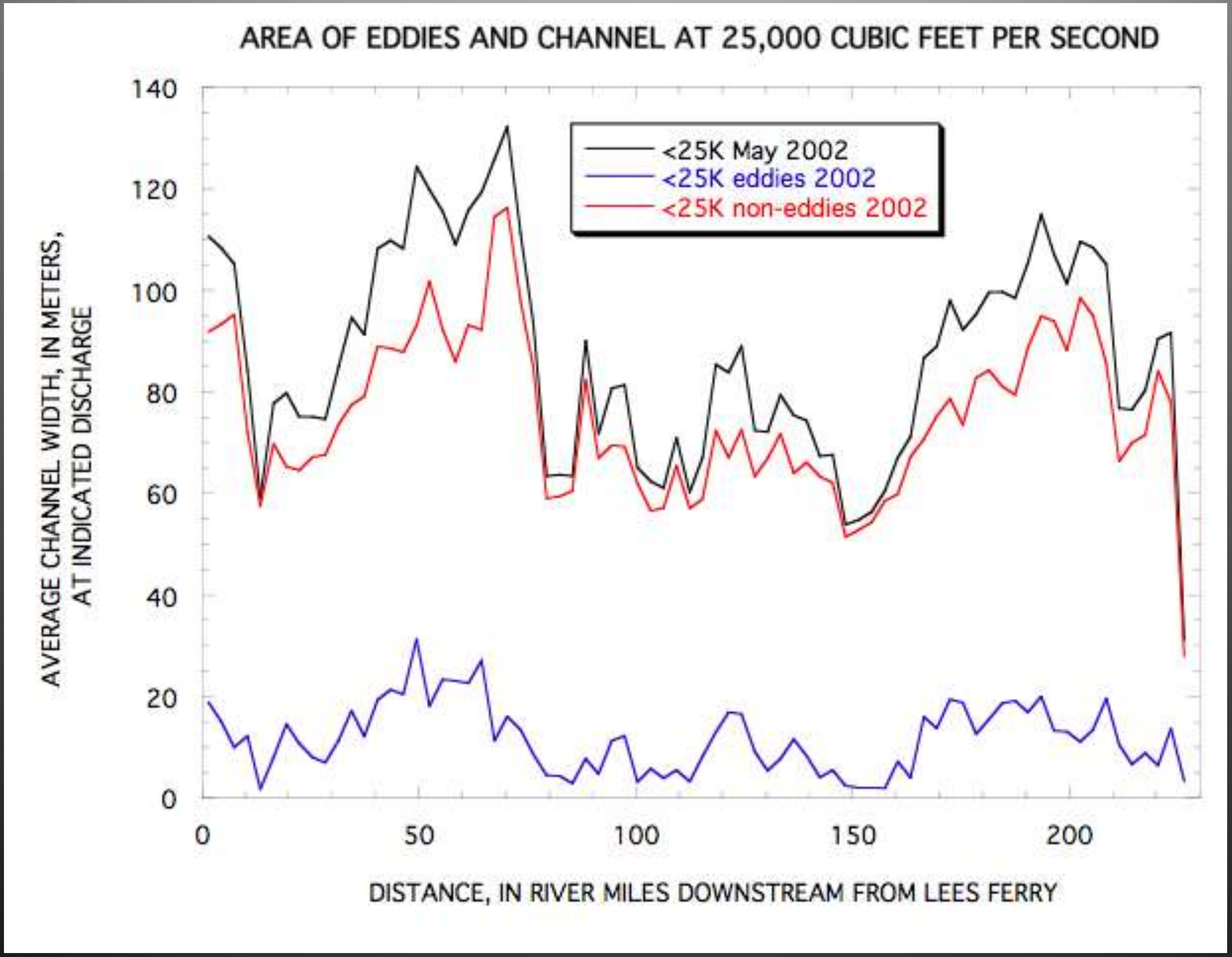
Stevens et al., 1995

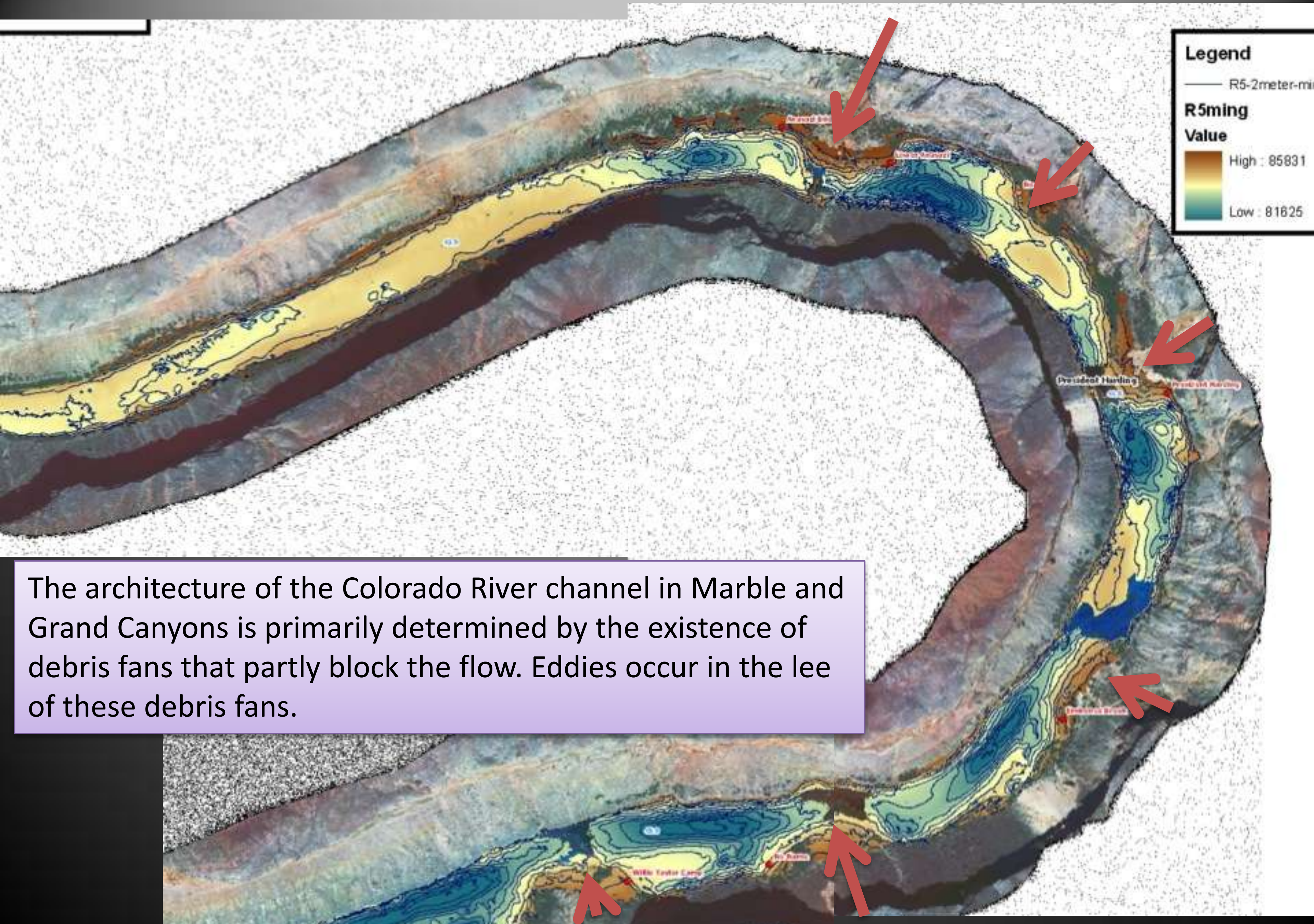




Schmidt and Grams, 2011

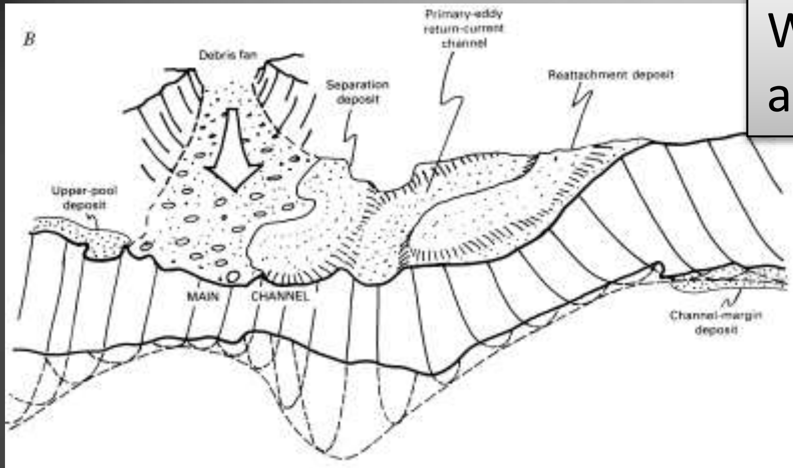
Valley architecture affects large-scale patterns in resource distribution





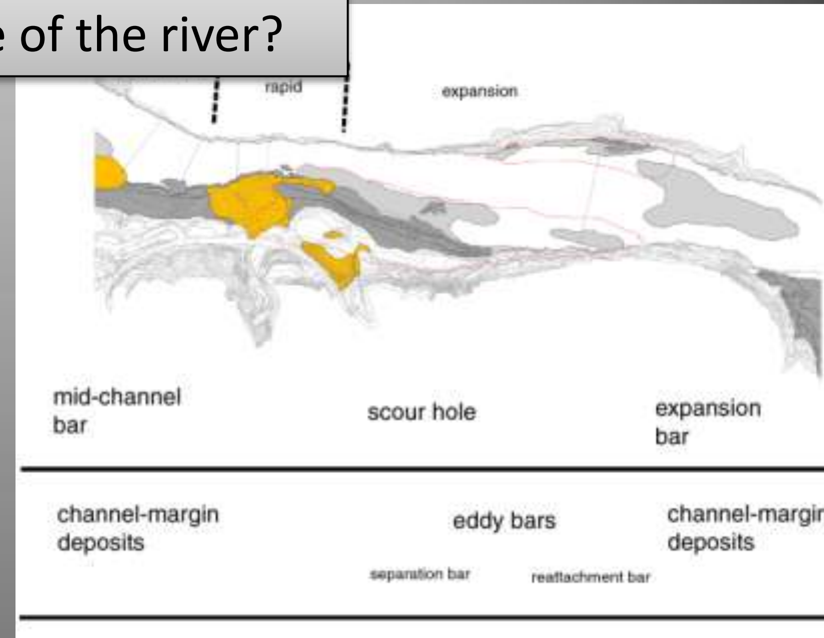
The architecture of the Colorado River channel in Marble and Grand Canyons is primarily determined by the existence of debris fans that partly block the flow. Eddies occur in the lee of these debris fans.

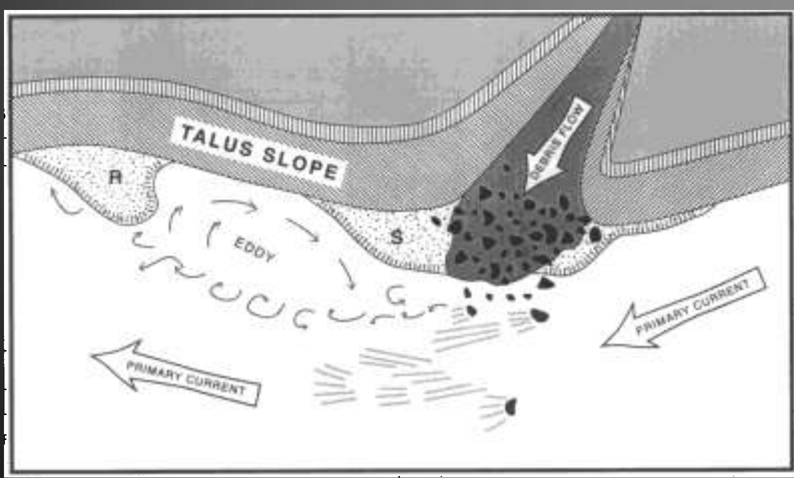
What is the small scale architecture of the river?



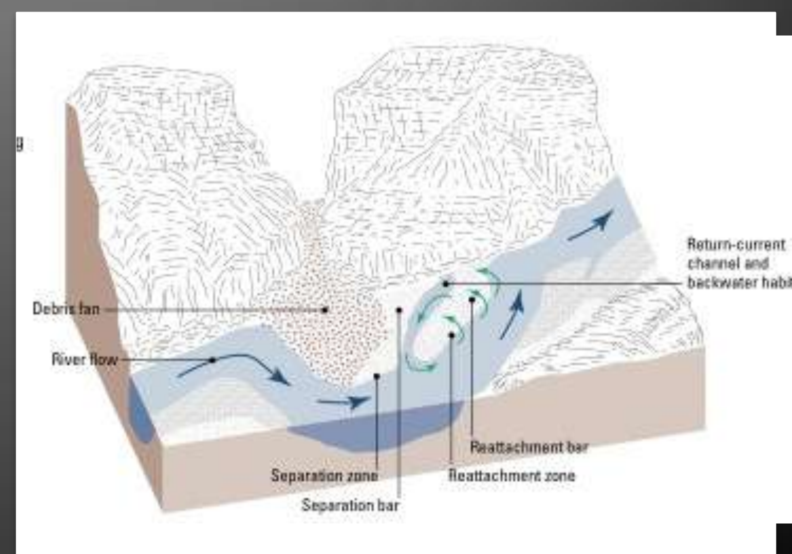
Schmidt and Graf, 1990

Schmidt and Rubin, 1995





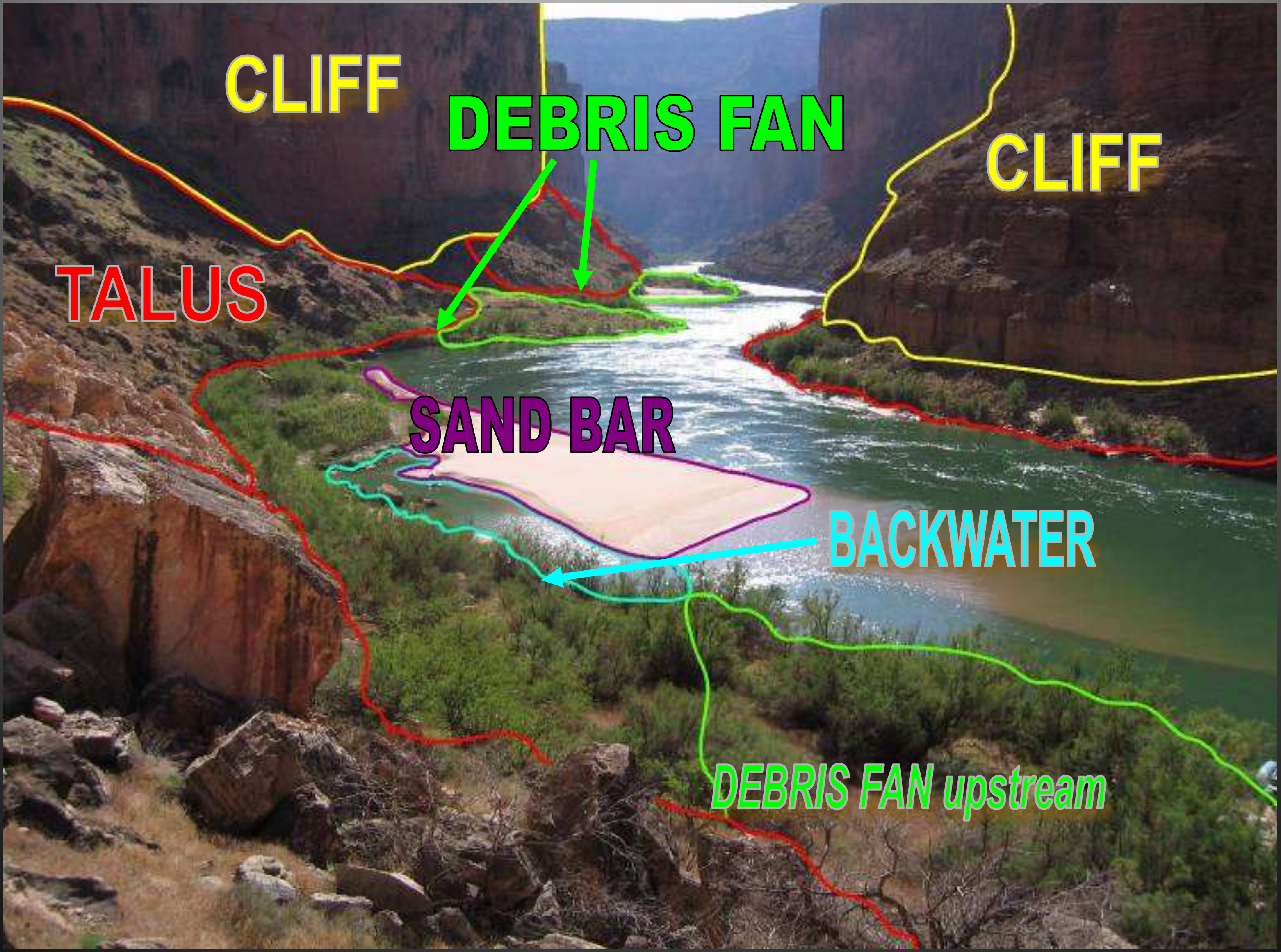
Bauer and Schmidt, 1993



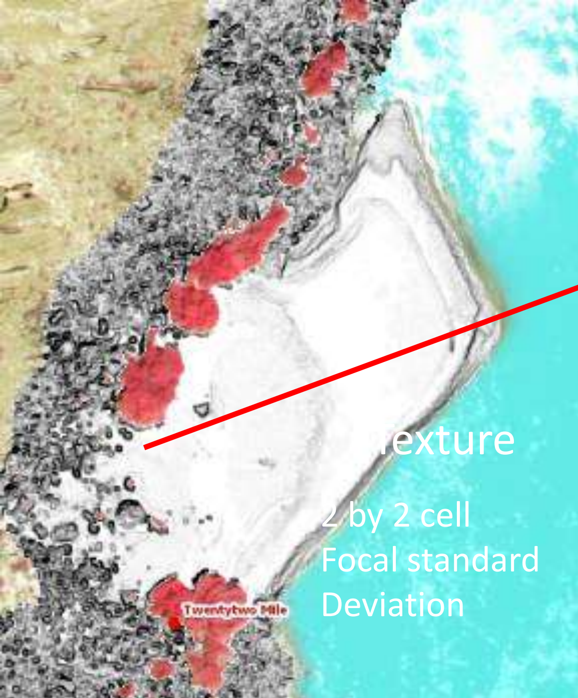
Schmidt and Grams, 2011

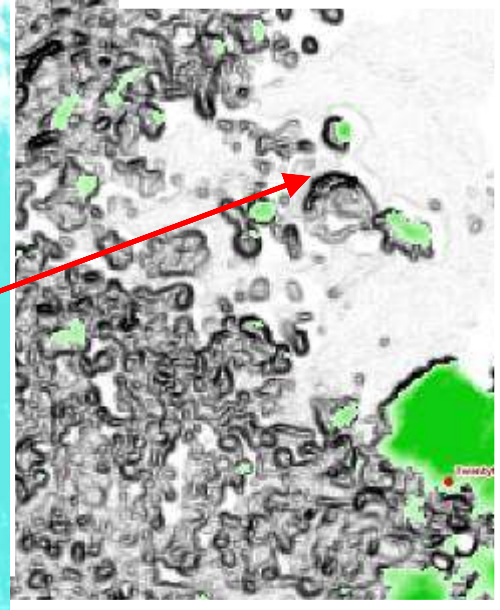
A fan-eddy complex includes (1) an area of ponded flow upstream from a debris fan, (2) a rapid opposite the debris fan, (3) an area where flow width expands and an eddy occurs, and (4) a gravel bar further downstream.

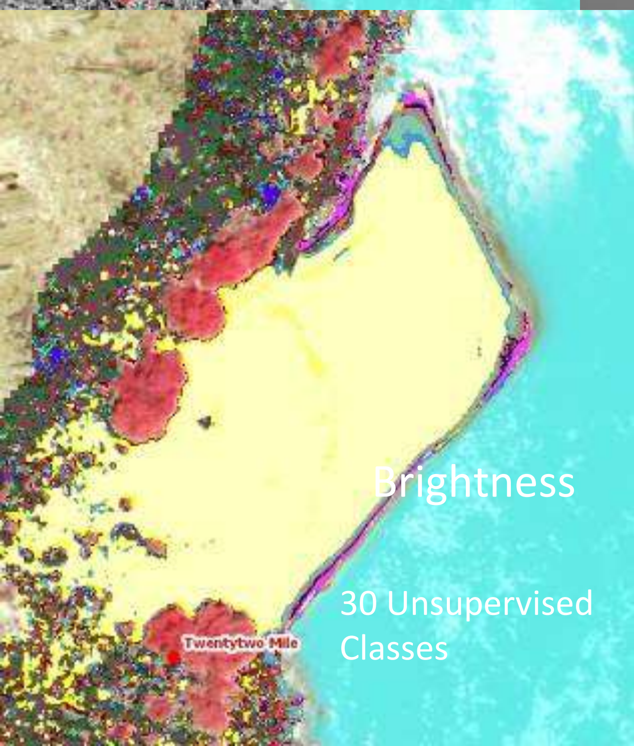
Large-scale geomorphic features can be recognized in aerial photographs and delineated as polygons for the entire river corridor.

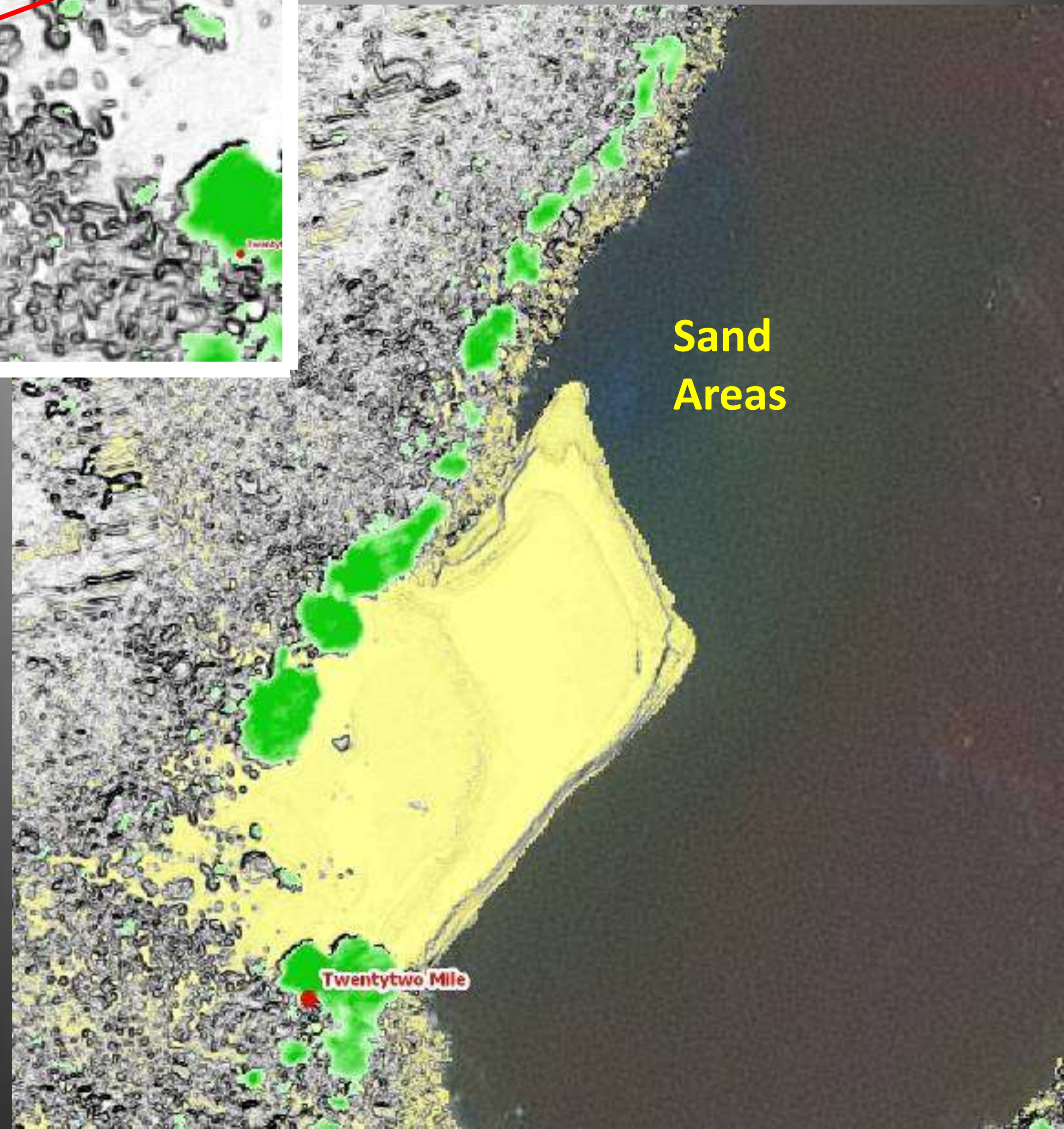


SAND CLASSIFICATION using remote imagery



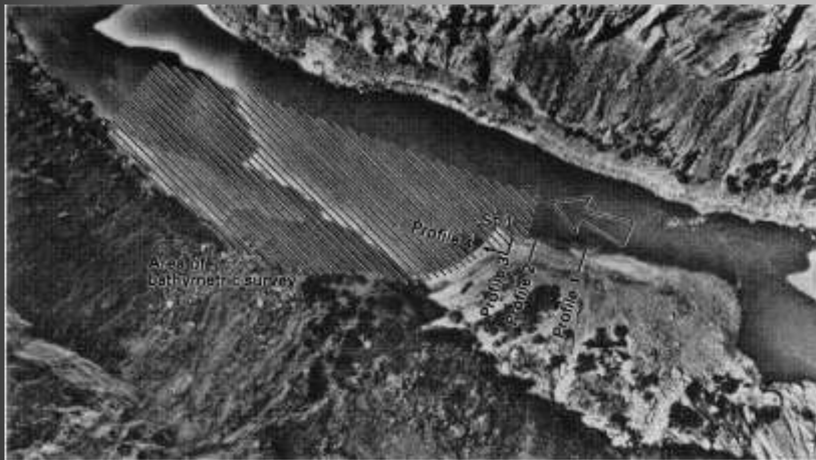




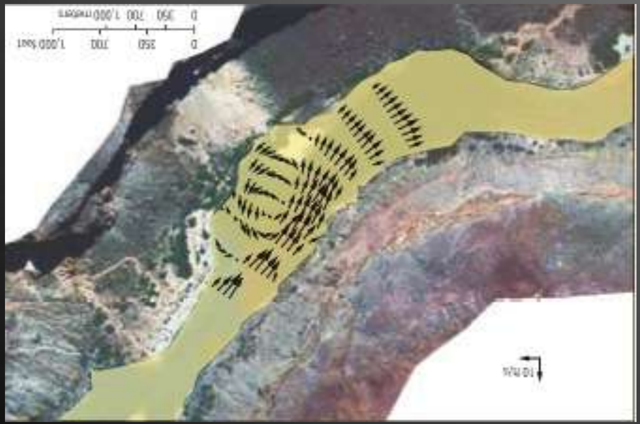


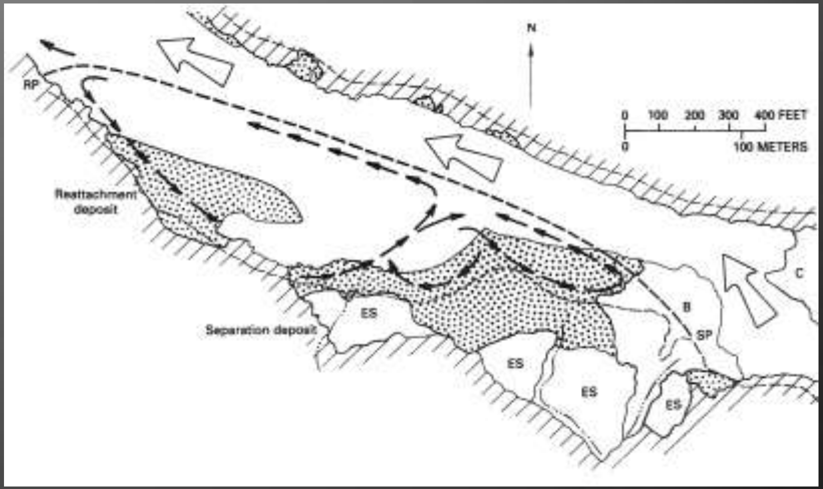
Flow patterns: what are they and how do they change?

Schmidt and Graf, 1990



Measured depth averaged horizontal velocities at peak flow during 2008 HFE



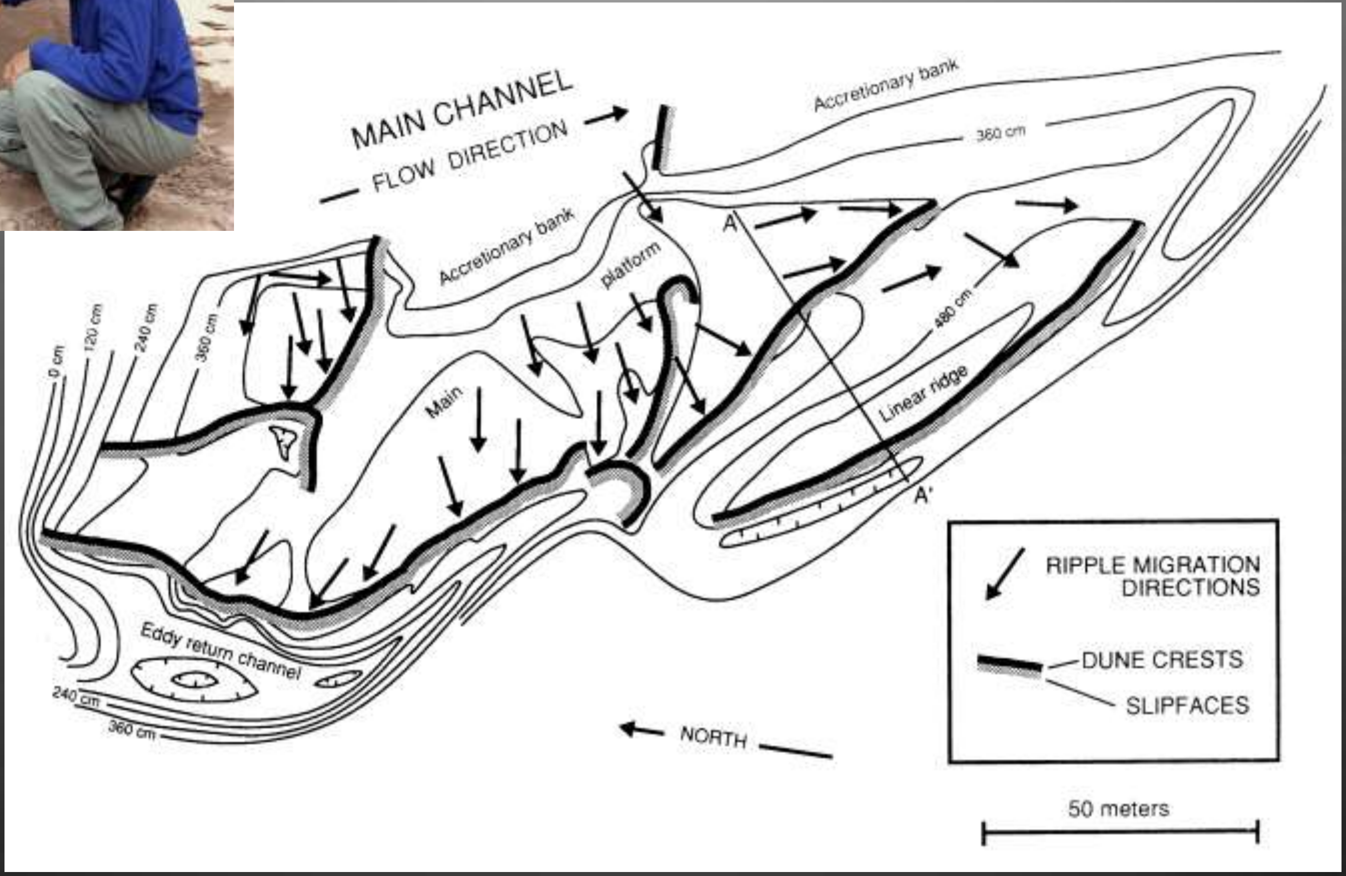


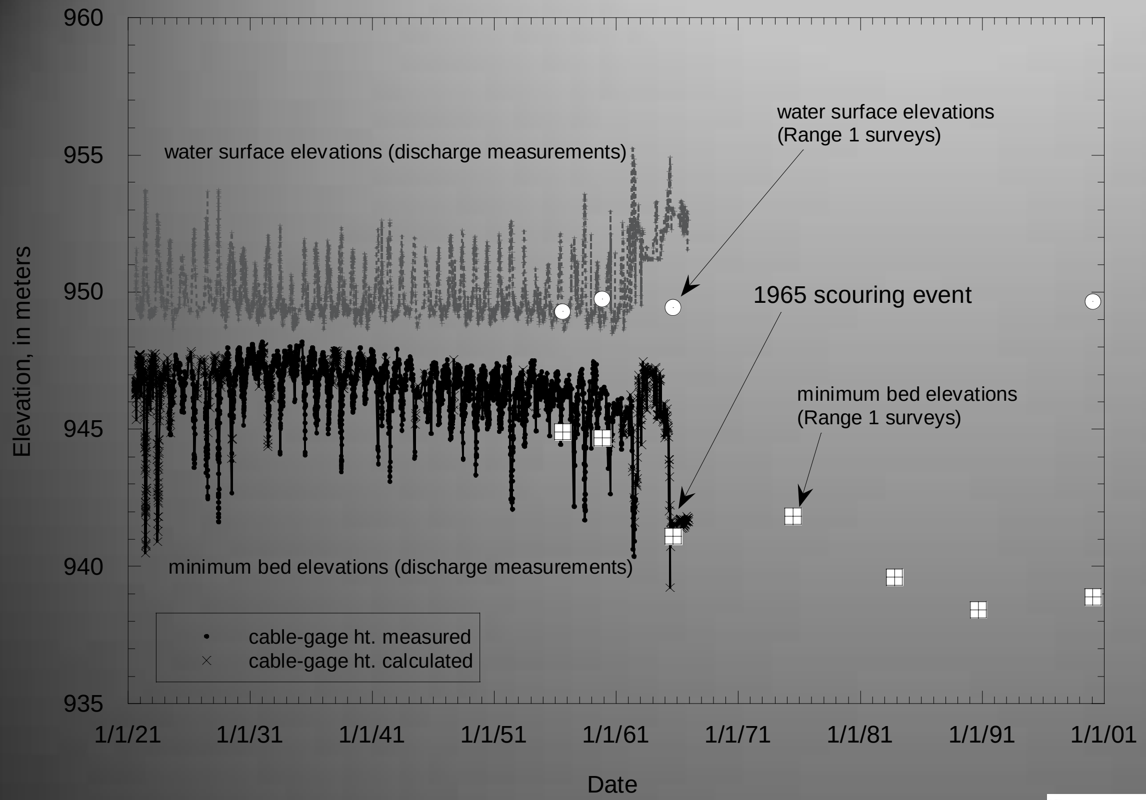
(Wright and Kaplinski, 2010)

Bar scale features include bar platform and return-current channel

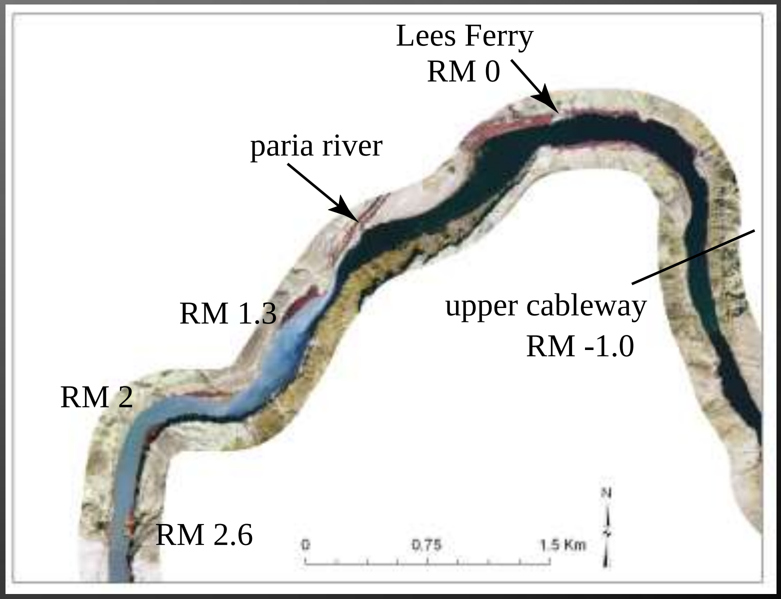
Sedimentary structures reflect flow field

(Rubin et al 1990)





What have been the long-term changes in the bed of the channel?

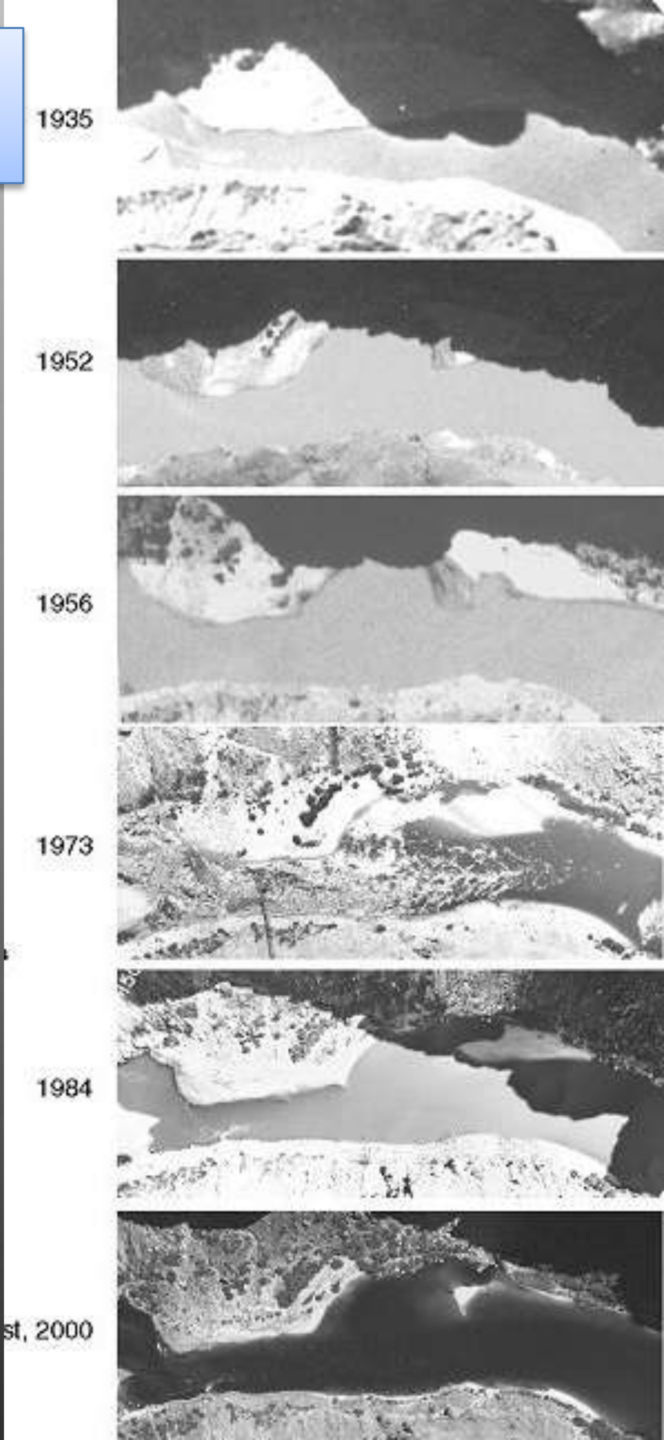


Changes at Eminence Break campsite, 57 km downstream from the dam

1952, Kent Frost

1995, USGS

Many sand bars have dramatically decreased in size



At some sites, sand bar changes have been minimal (Grapevine Camp river mile 81.8L)

Late afternoon, August 7, 1976 (~daily mean 9,000 ft^3/s)

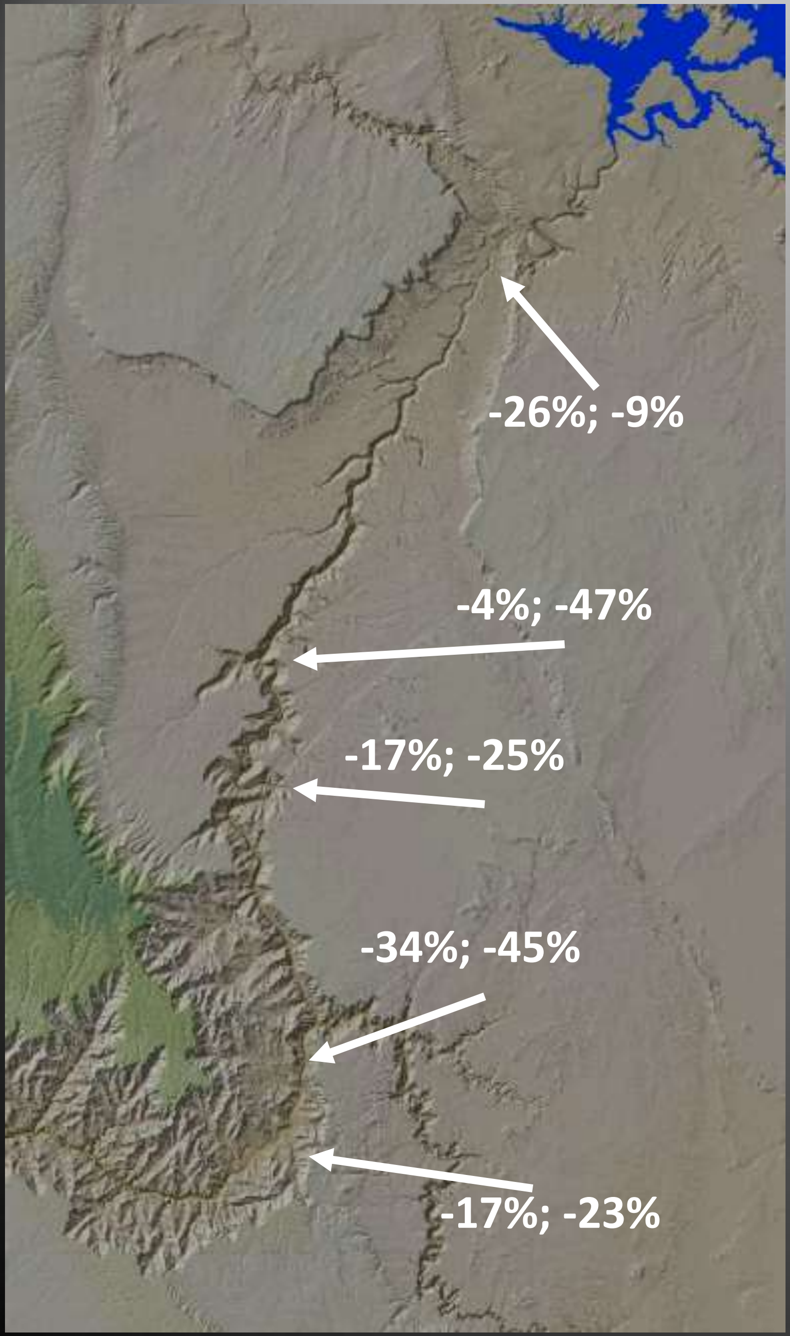
1300 August 7, 1985 (~21,300 ft^3/s)

1645 January 24, 1989 (~13,600 ft^3/s)

0945 April 6, 2008 (~10,400 ft^3/s)

Grapevine, RM 81.76L, Downstream View: 1976, 1985, 1989 sand levels shown in 2008 photo

0945 April 6, 2008 (~10,400 ft^3/s)



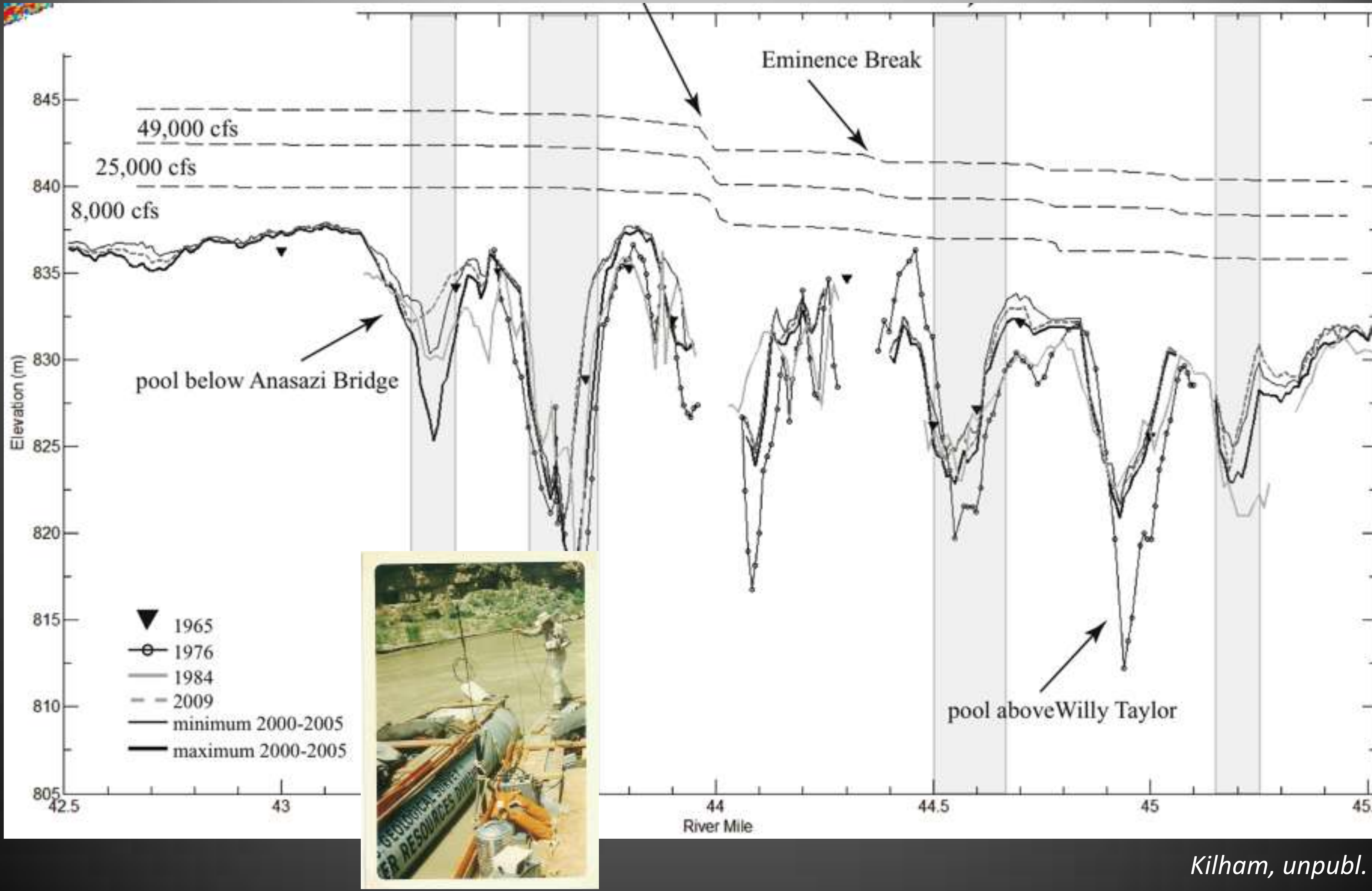
Based on aerial photograph comparison, the average area of eddy bars in the 1990s was at least 25% smaller than the average pre-dam conditions.

>95% reduction in sand supply has led to ~25% reduction in sand bar size ????

change in the area of all sand

change in sand in the post-dam flood zone

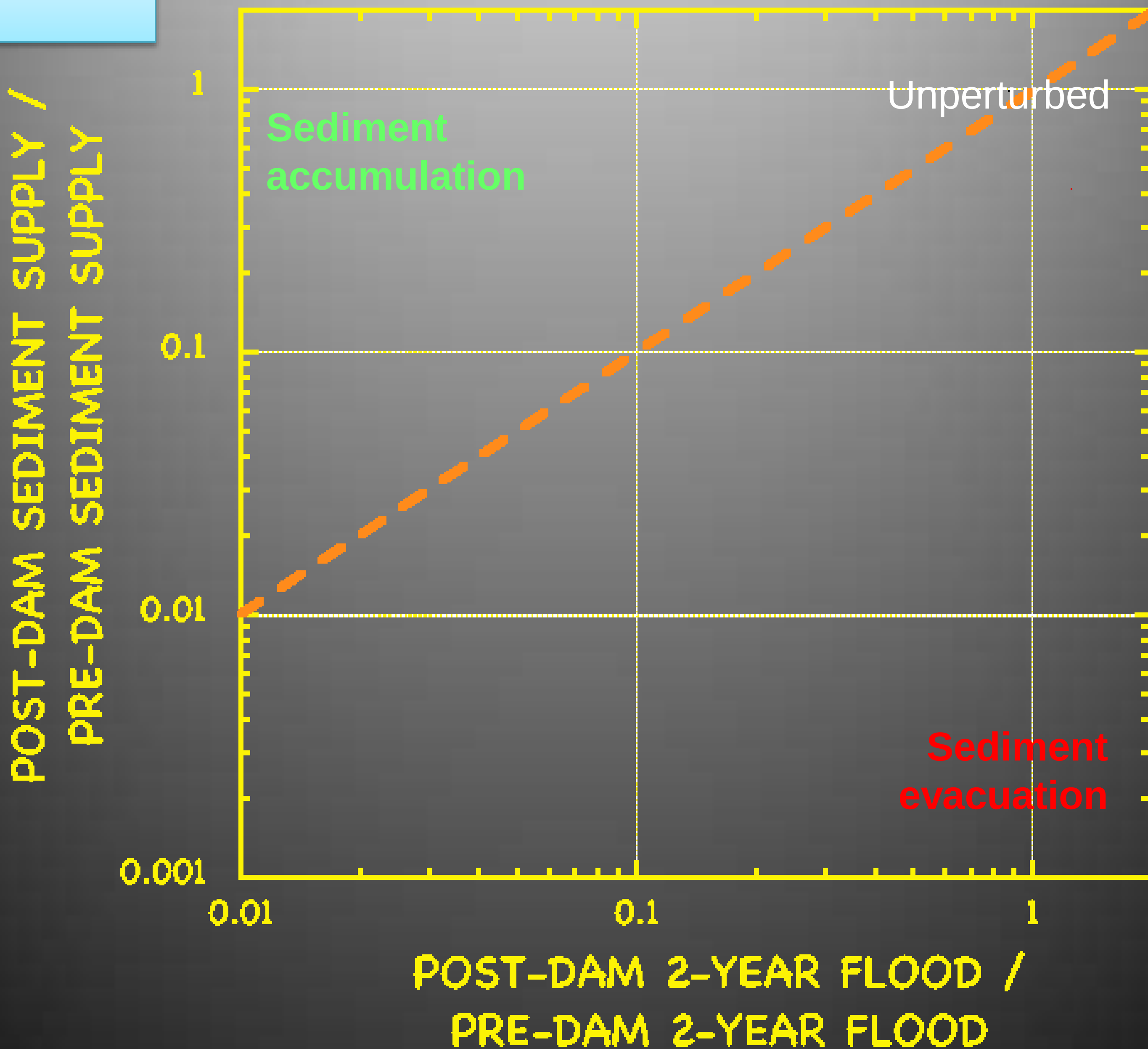
(Schmidt et al, 2004)



Kilham, unpubl.

The old longitudinal profiles of the river have been compared with recent traces

Returning to the big picture



Three Metrics to Describe Channel Change below Dams

- Perturbation of the predam sediment mass balance
  - Assessing shifts towards deficit or surplus

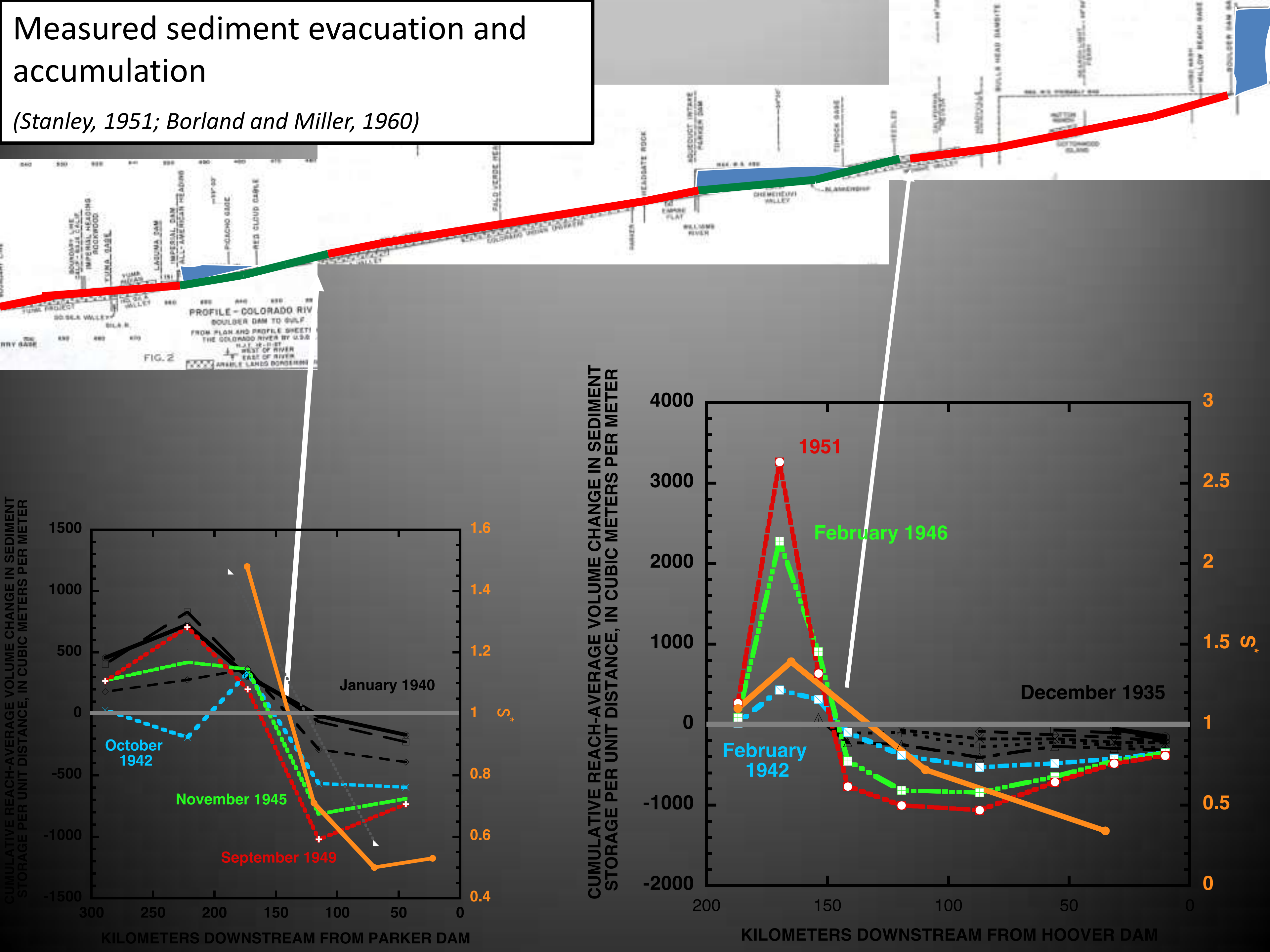
- Post-dam bed incision

- Potential for changes in width

Schmidt and Wilcock, 2008

Measured sediment evacuation and accumulation

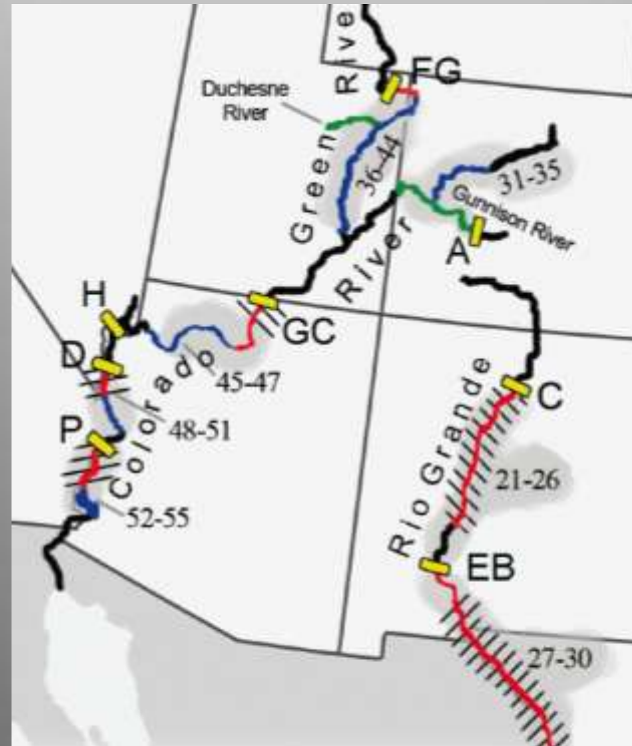
(Stanley, 1951; Borland and Miller, 1960)



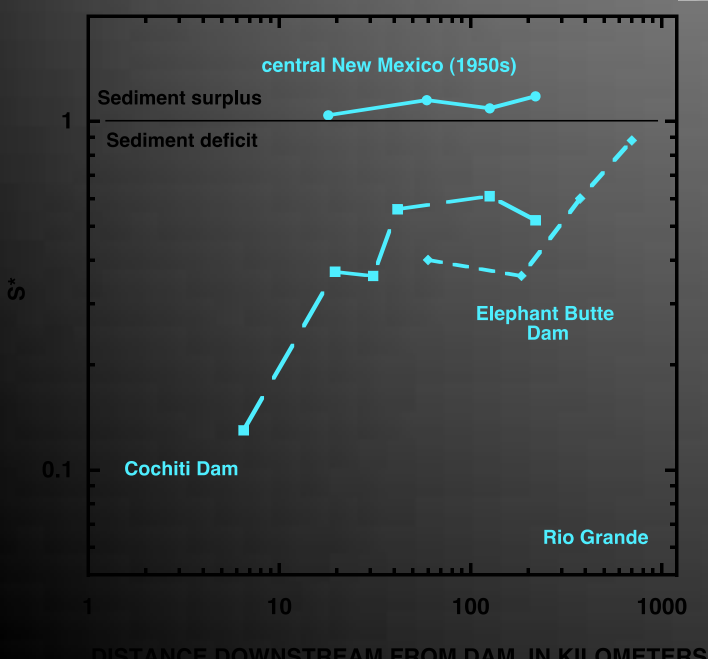
Perturbation of sediment mass balance caused by dams

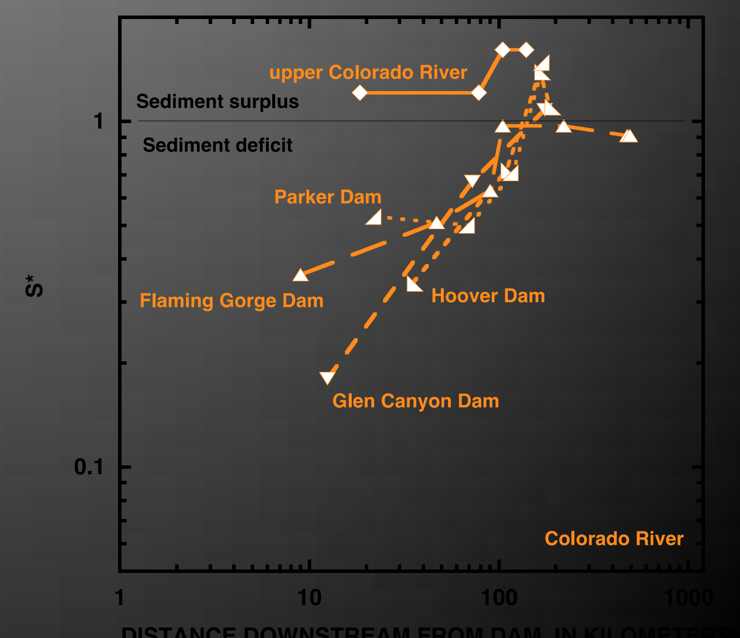
(red = S<1; sediment deficit)*
(green = S>1; sediment surplus)*
(blue= sediment balance indeterminate)

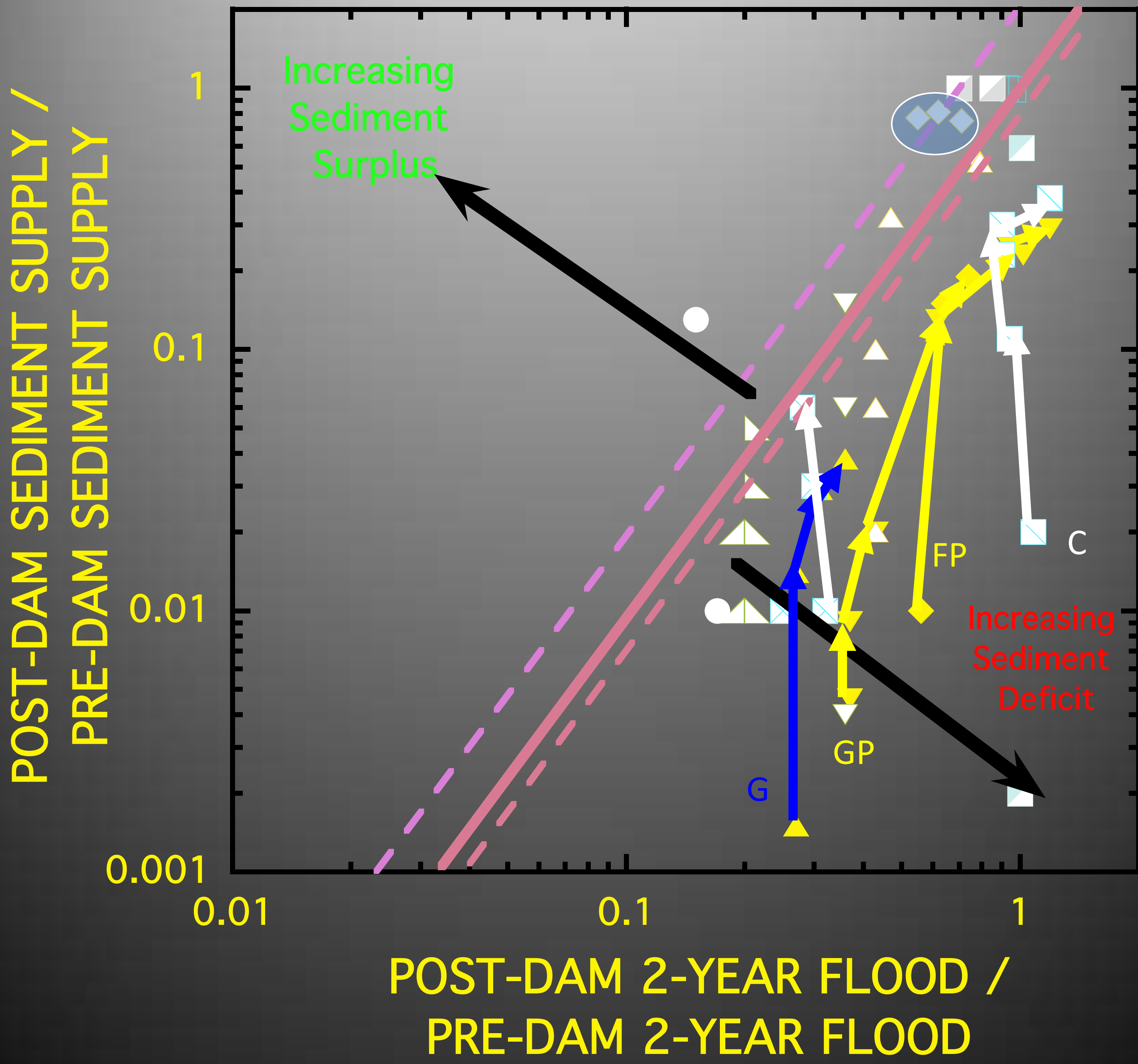
(hachure indicates zone of bed incision)



(Schmidt and Wilcock, 2008)

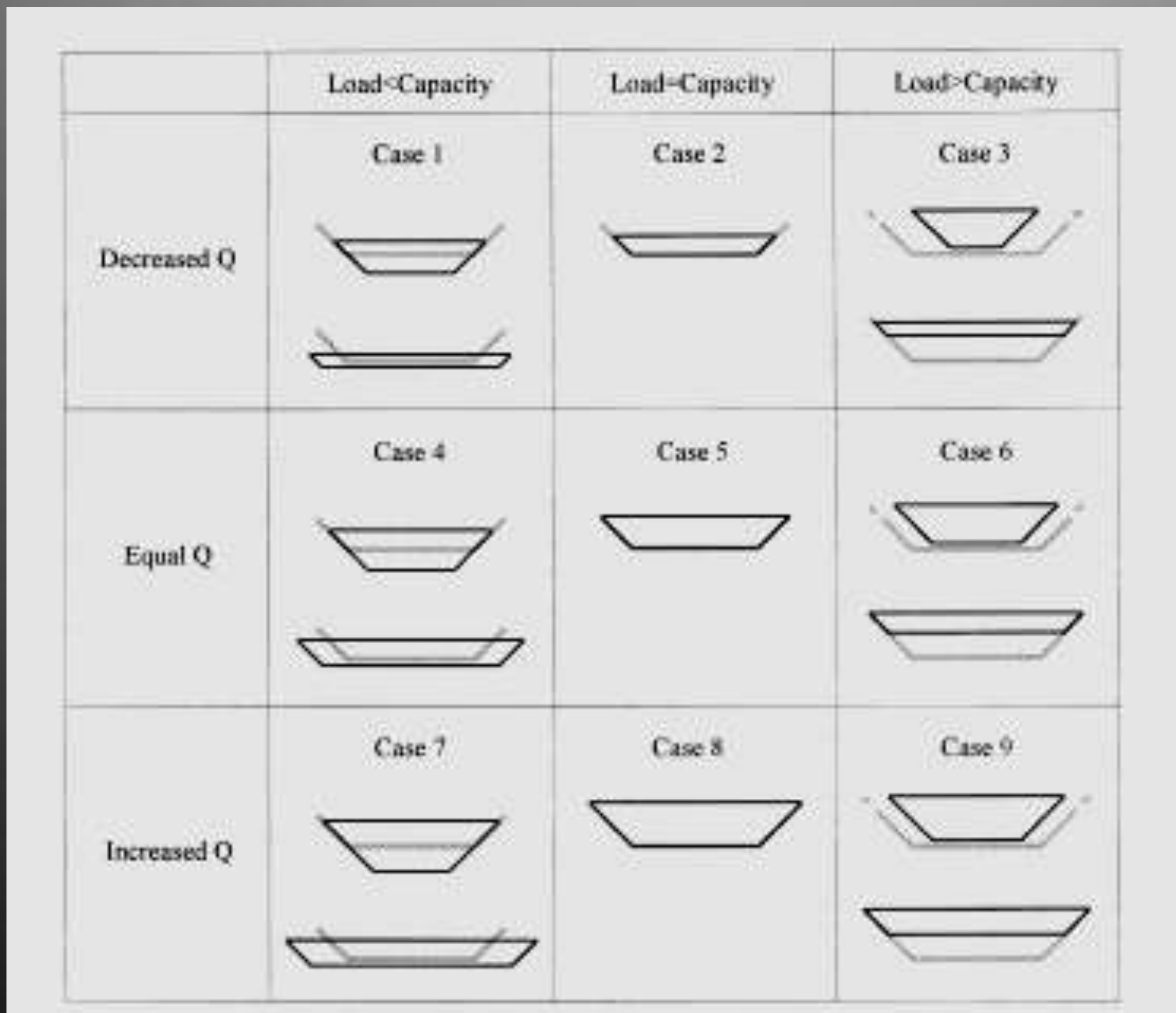






Increasing Sediment Surplus
Increasing Sediment Deficit
G
GP
FP
C
1
0.1
0.01
0.001
0.01
0.1
1
POST-DAM SEDIMENT SUPPLY / PRE-DAM SEDIMENT SUPPLY
POST-DAM 2-YEAR FLOOD / PRE-DAM 2-YEAR FLOOD

Anticipating attributes of channel change

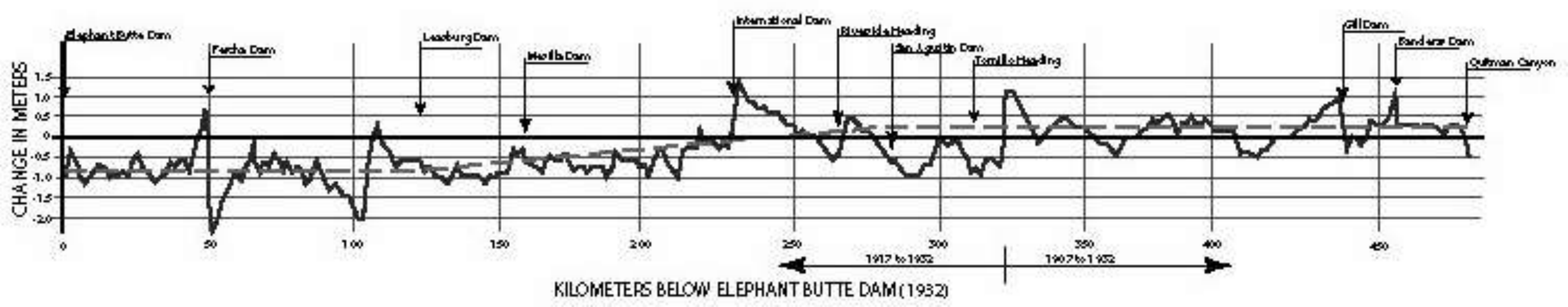


(Brandt, 2000)

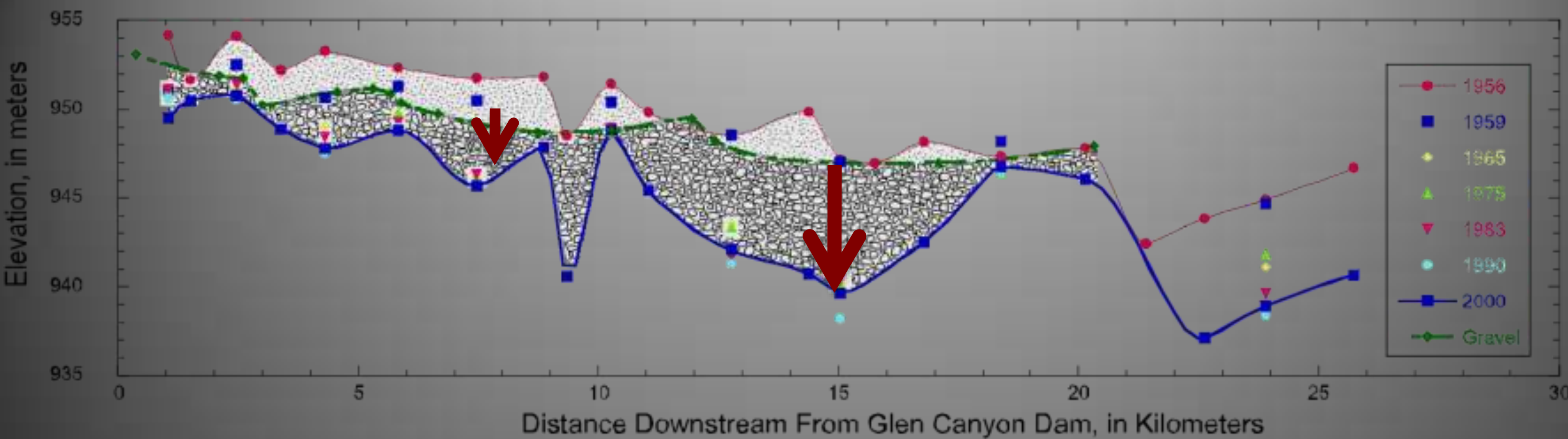
Pattern of channel change downstream from Elephant Butte Dam is typical of the pattern of change below all dams

Downstream from Elephant Butte Dam, the upper river **incised its bed** as much as 1 m within 225 km downstream from Elephant Butte Dam between ~1917 and ~1933. Downstream from El Paso/Juarez, the bed **aggraded** about 0.25 m.

(Stevens, 1938)



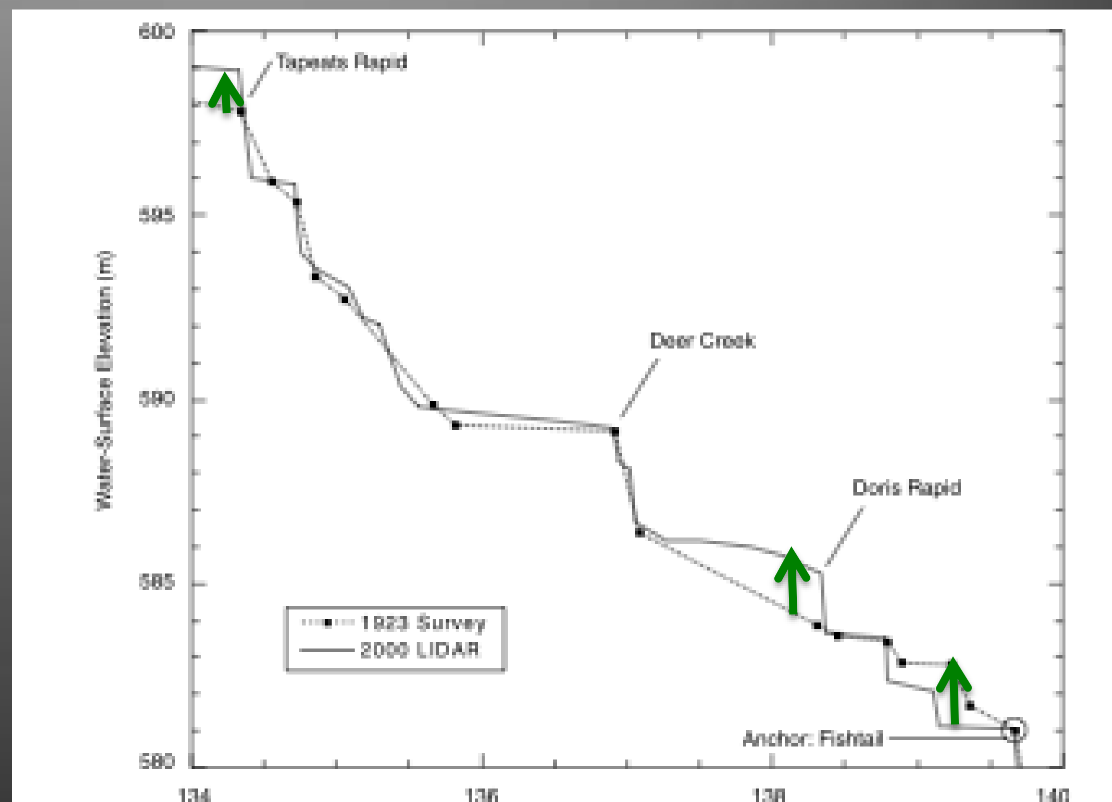
In Glen Canyon, sediment deficit, bed incision occurred ….



Grams et al., 2007

… and conversion of a sand bed to a cobble bed.

Coarse bouldery rapids prevent bed adjustment in Grand Canyon. With low sediment supply and steep channel slope, mass balance deficit remains and available fine sediment is efficiently removed from system.



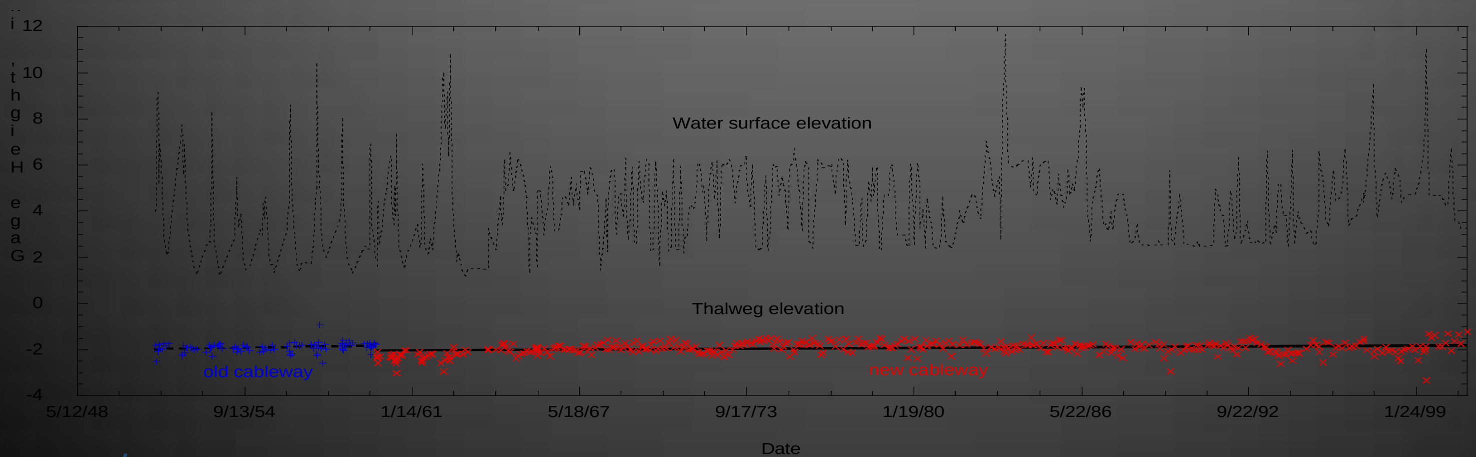
Magirl et al., 2005

S = 0.67 (for fines)*

S > 1 (for gravel)*

Green River immediately below Flaming Gorge Dam

Eroded eddy sand bar



(Grams and Schmidt, 2005)

No change in bed elevation at gaging station

Channels also changes in width

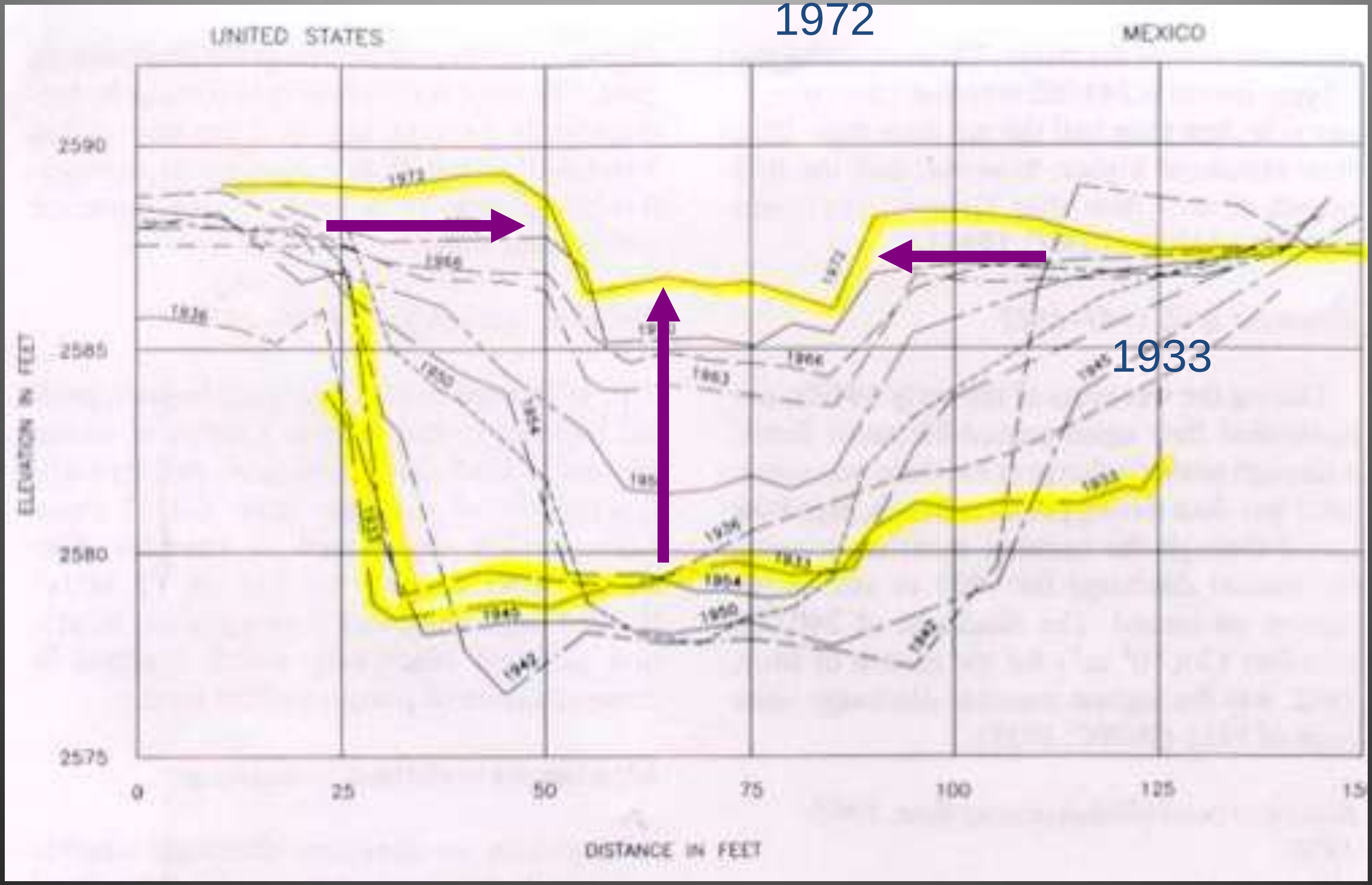
It is difficult to predict the magnitude of narrowing

Narrowing with sediment surplus and no bed incision
Narrowing with sediment surplus and bed incision

Narrowing with equilibrium conditions

Narrowing with deficit conditions and no bed incision
Narrowing with deficit conditions and bed incision

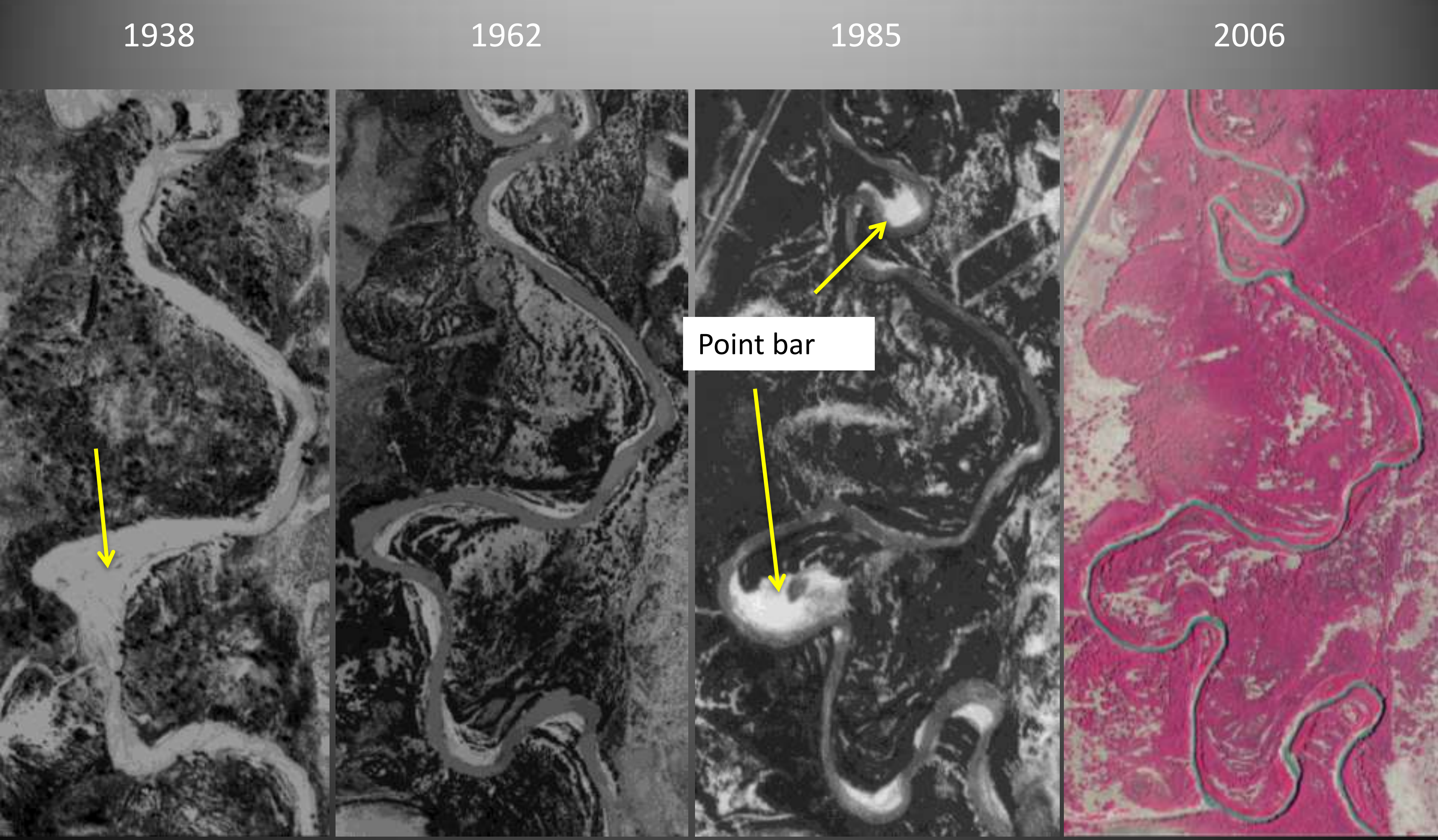
Sediment surplus – narrowing and bed aggradation



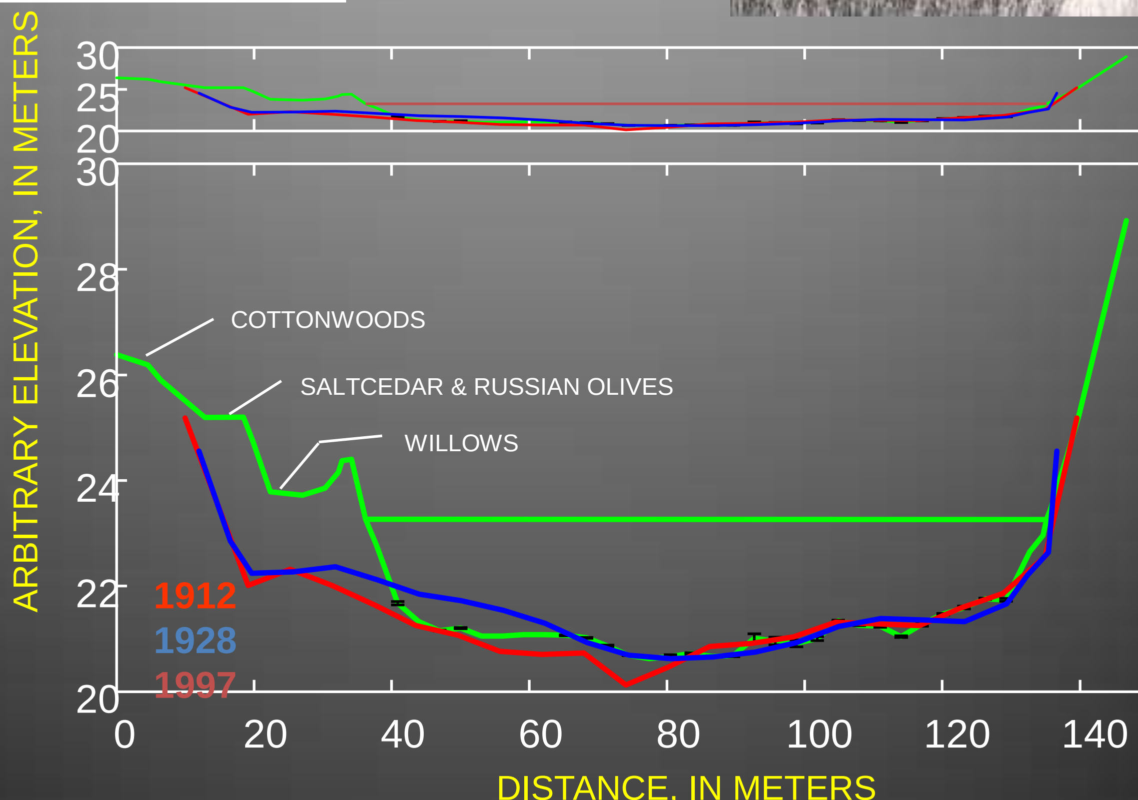
The Rio Grande above the Rio Cochos, near Presidio

Everitt (1993)

Extreme narrowing – San Rafael River S* > 1 with bed incision



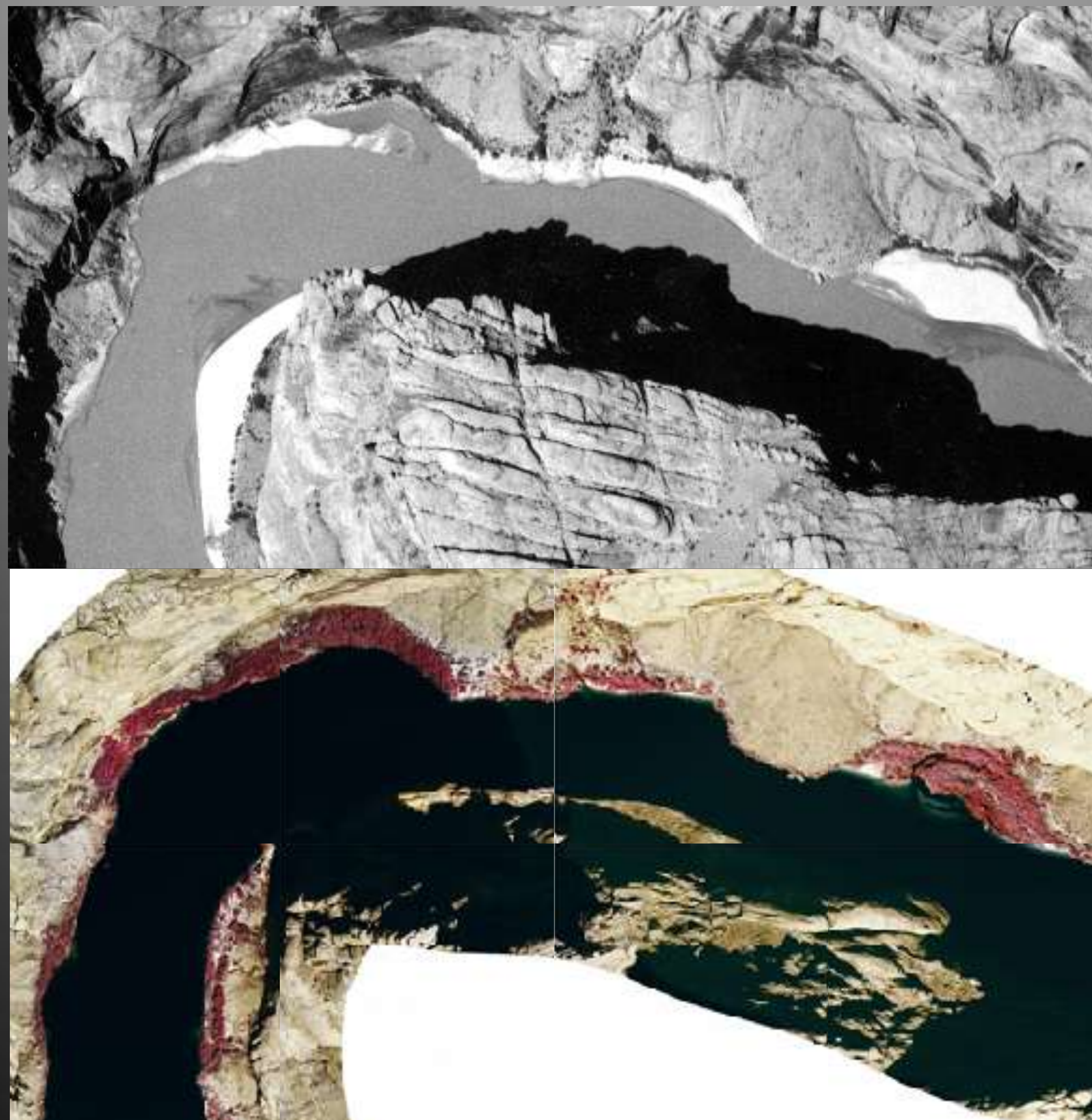
Green River, near Green River, UT



15% narrowing

(Allred and Schmidt, 1999)

These deposits are stabilized by riparian vegetation



1952

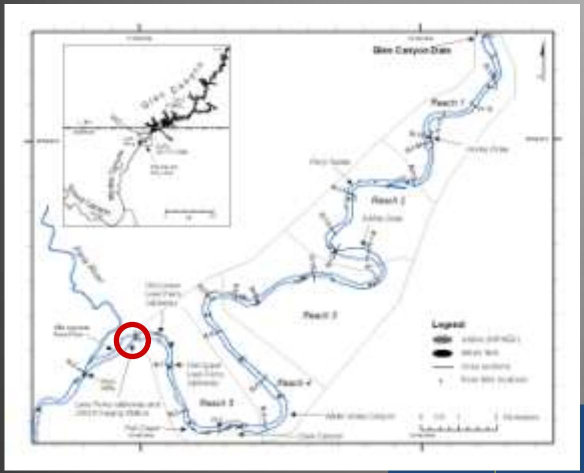
1998

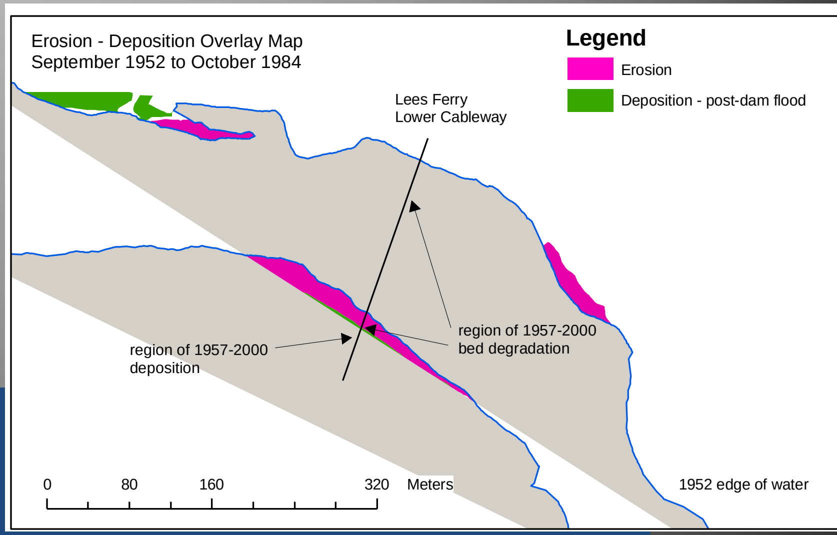
Bed degradation → Perched deposits on channel margins

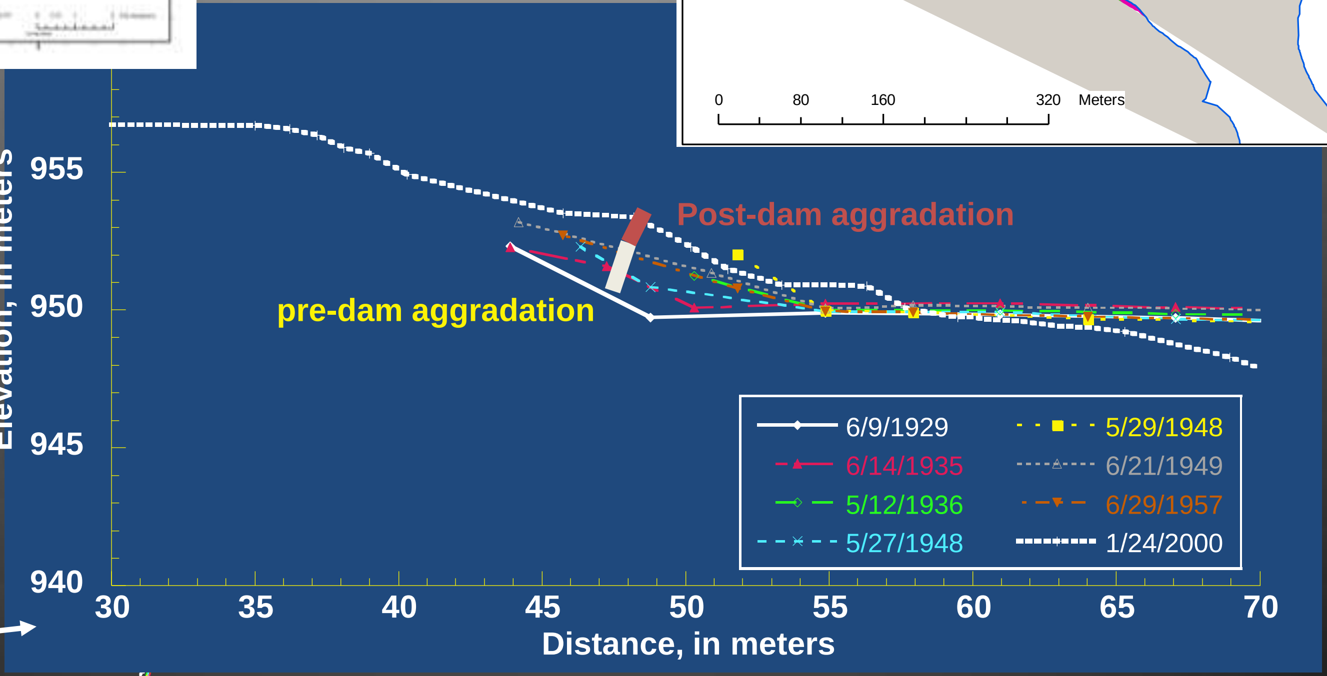
1889

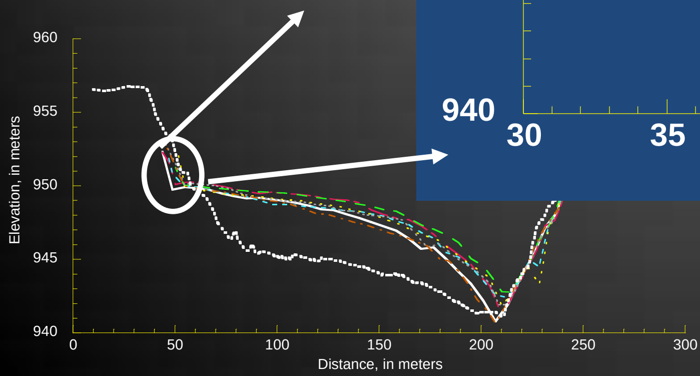
1992

Styles of channel adjustment in segments with degrading bed and **stable** stage-discharge relation: Bed Scour and bank deposition

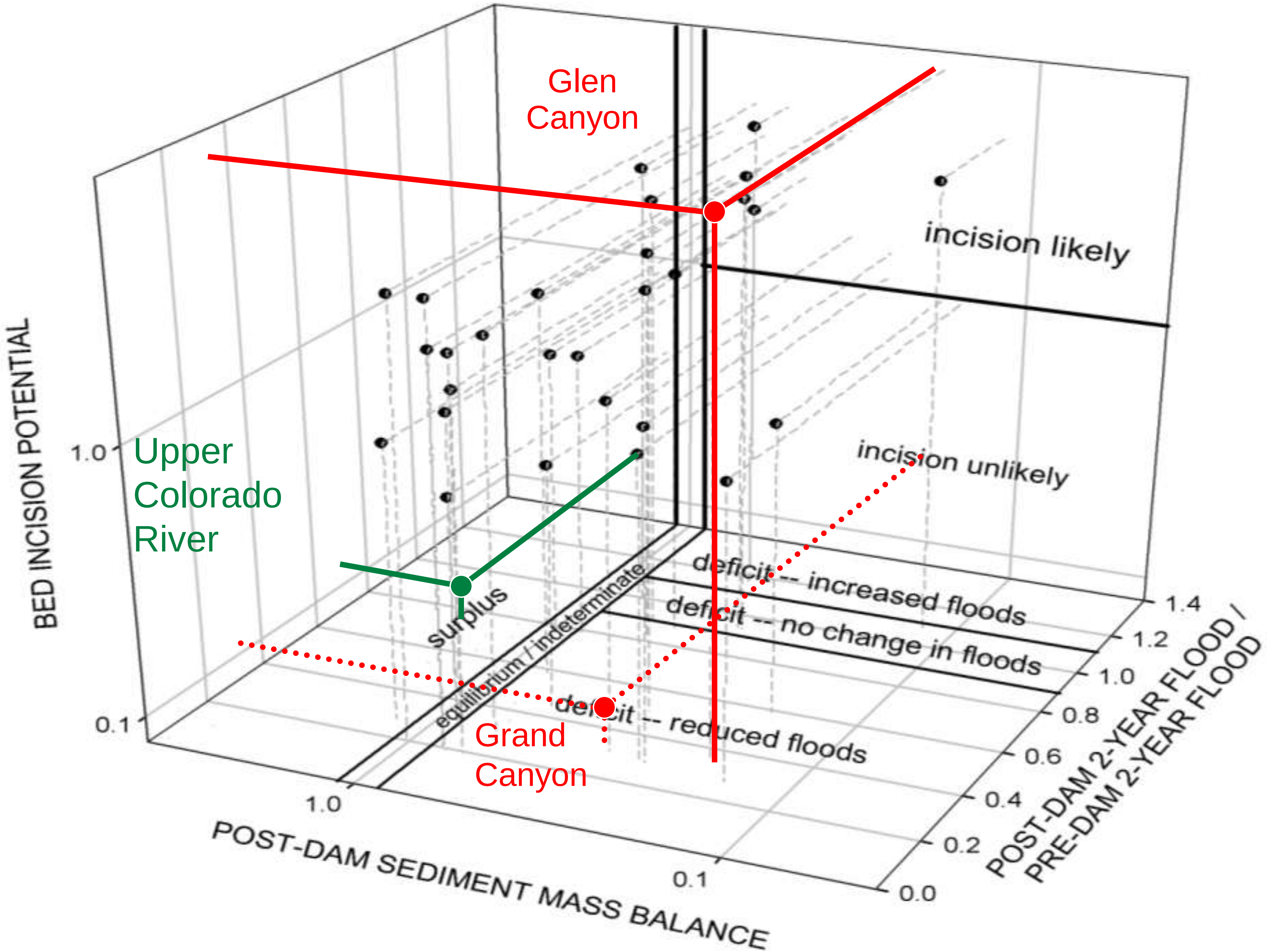




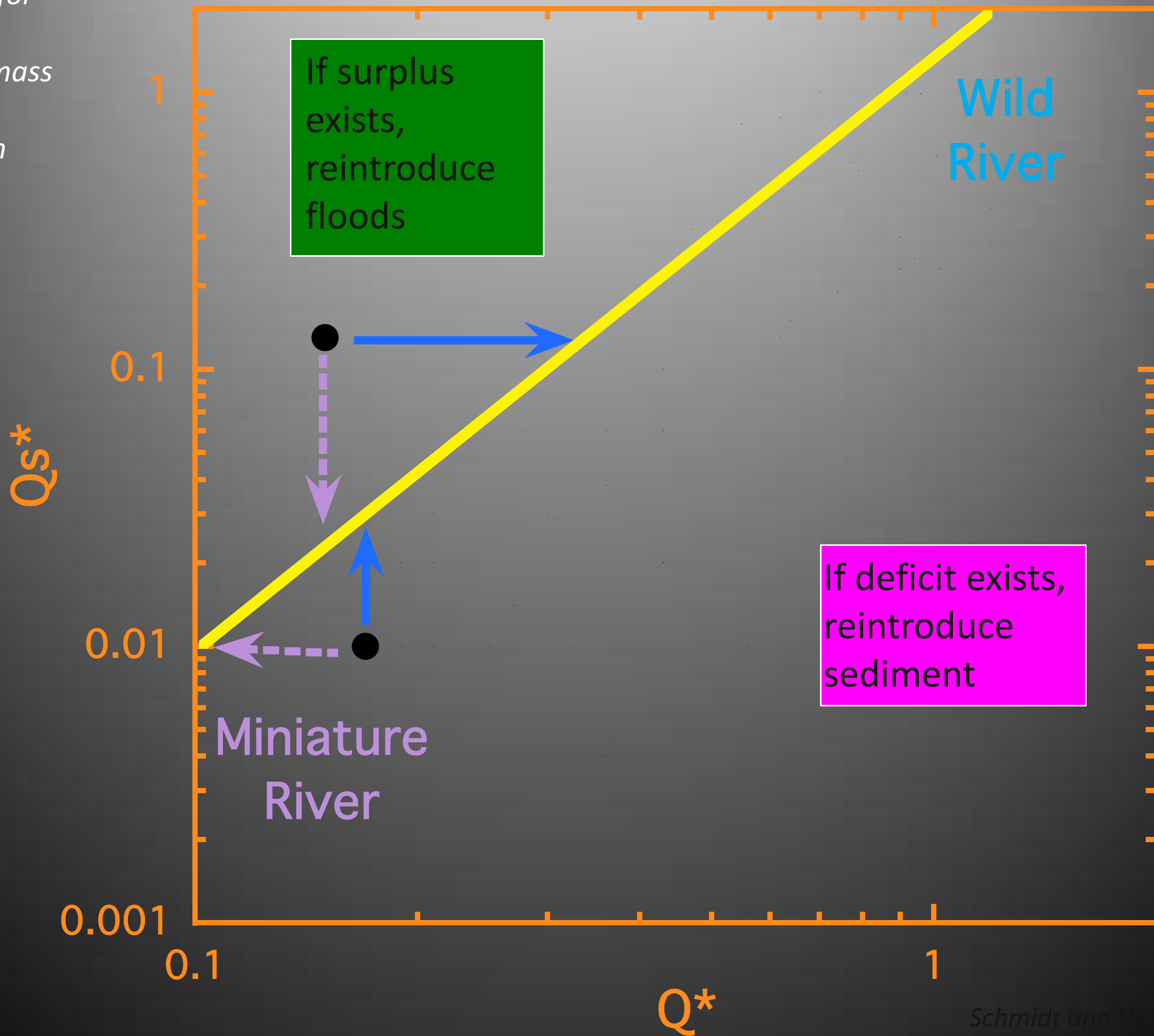




Lees Ferry, Lower Cableway


Glen
Canyon
incision likely
incision unlikely
Upper
Colorado
River
surplus
equilibrium / indeterminate
deficit -- increased floods
deficit -- no change in floods
deficit -- reduced floods
Grand
Canyon
BED INCISION POTENTIAL
1.0
0.1
POST-DAM SEDIMENT MASS BALANCE
1.0
0.1
POST-DAM 2-YEAR FLOOD /
PRE-DAM 2-YEAR FLOOD
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

Strategies for restoring sediment mass balance equilibrium



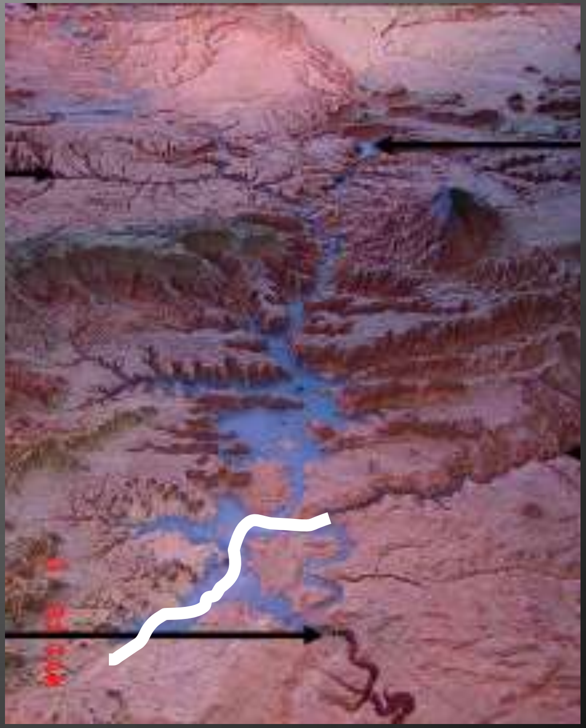
Schmidt and Wilcock, 2008

The costs of adding sediment from Lake Powell into Grand Canyon

Addition of 4.3 x 10^6 Mg/yr by dredging and pipeline; *appraisal level cost estimates*

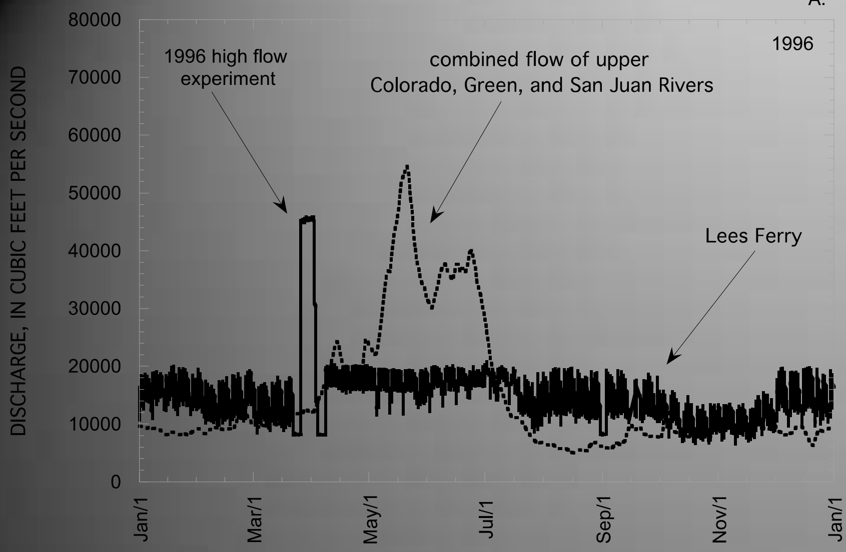
Slurry pipeline Navajo Canyon to Glen Canyon Dam ($220 million capital costs; $6.6 million annual operating cost)

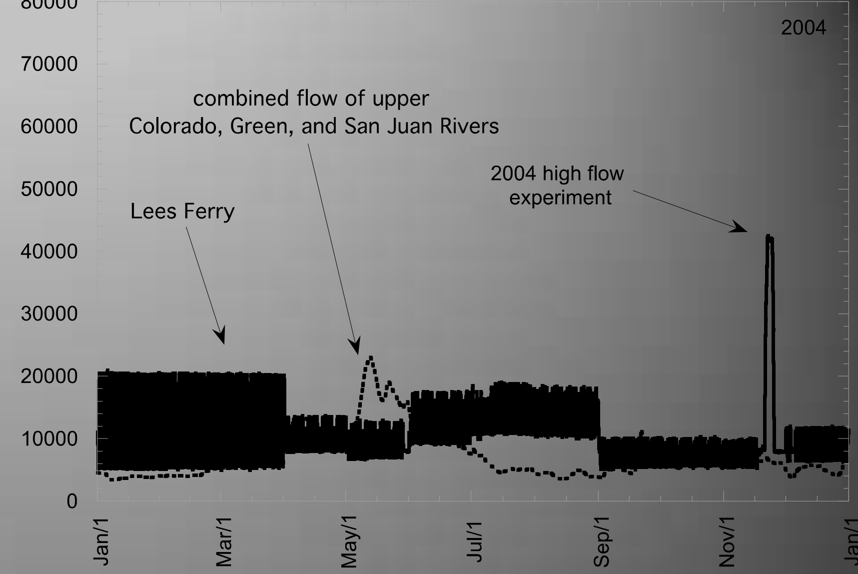
Slurry pipeline Navajo Canyon to Lees Ferry ($430 million capital costs; $17 million annual operating cost)



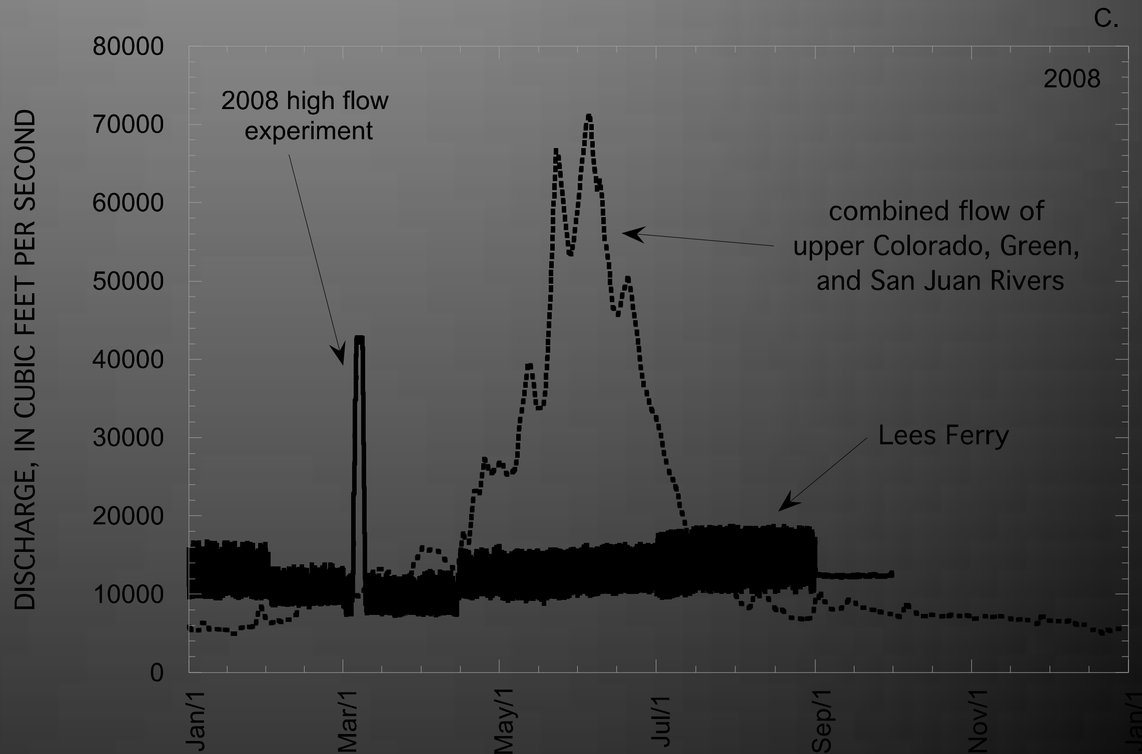
$44 million/yr is EIS estimate of cost reduced fluctuating flows

Randle et al, 2007



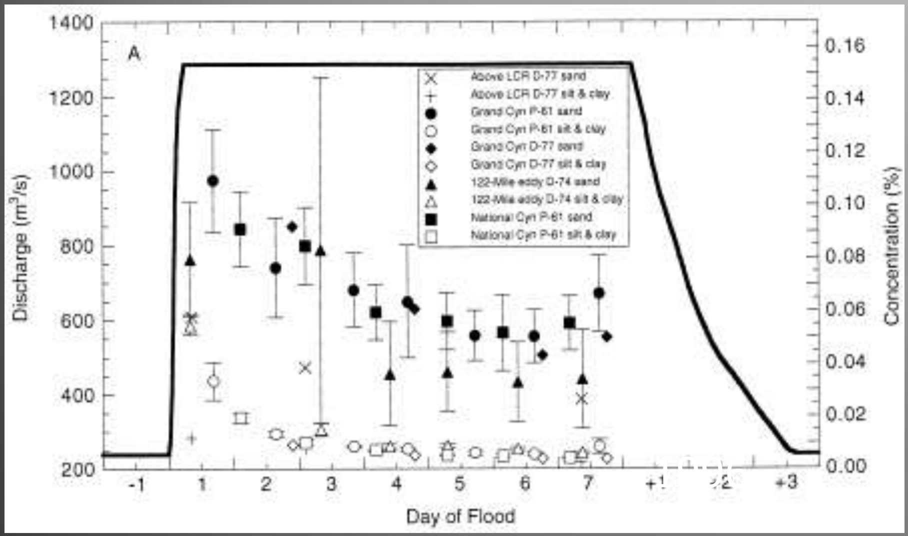


Constraints on reintroducing clear-water floods into a sediment deficit system



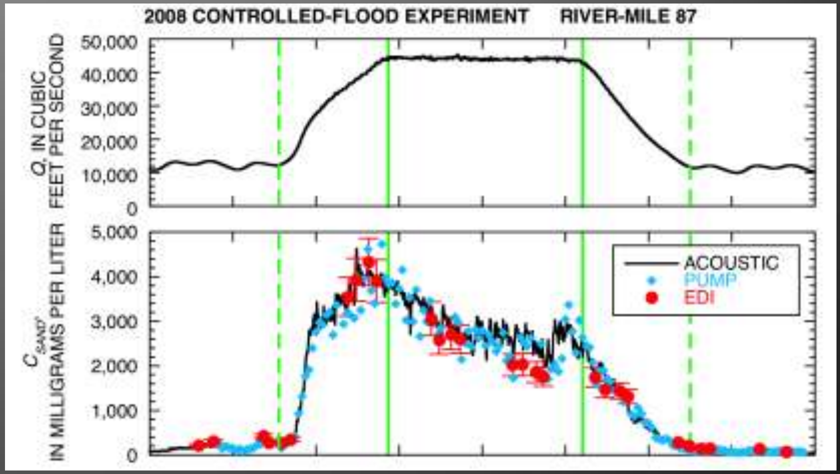
Natural and actual Lees Ferry flows

Controlled floods quickly deplete the available supply.



Change in suspended sediment concentration with time during two large dam releases

Topping, Rubin, various papers

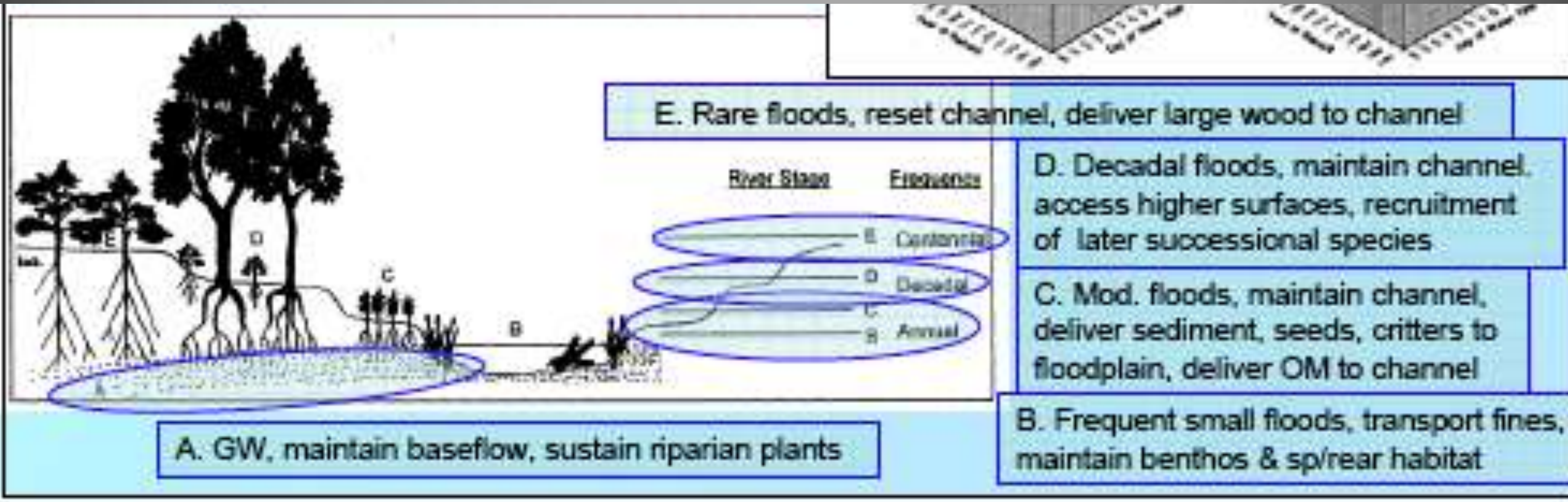


2008

Topping et al., 2010

The science of establishing environmental flows

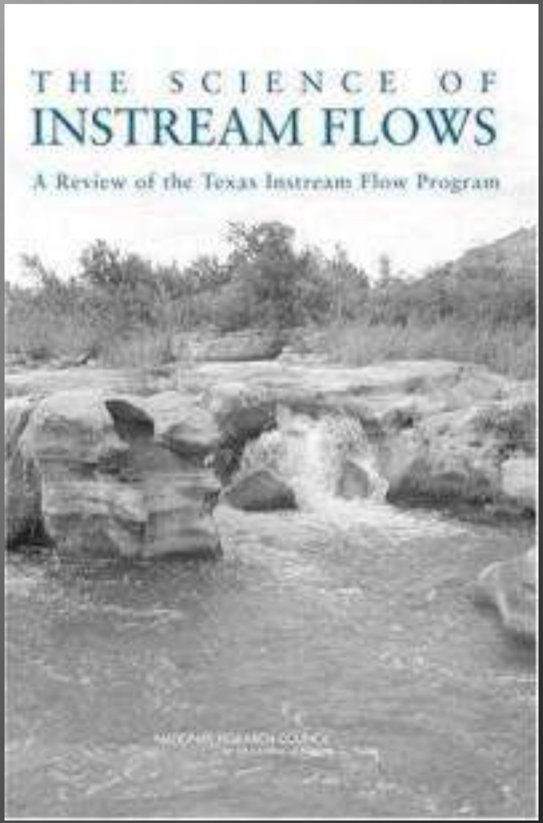
Each part of the flow regime plays a different ecological role: magnitude, duration, frequency, duration, timing and predictability

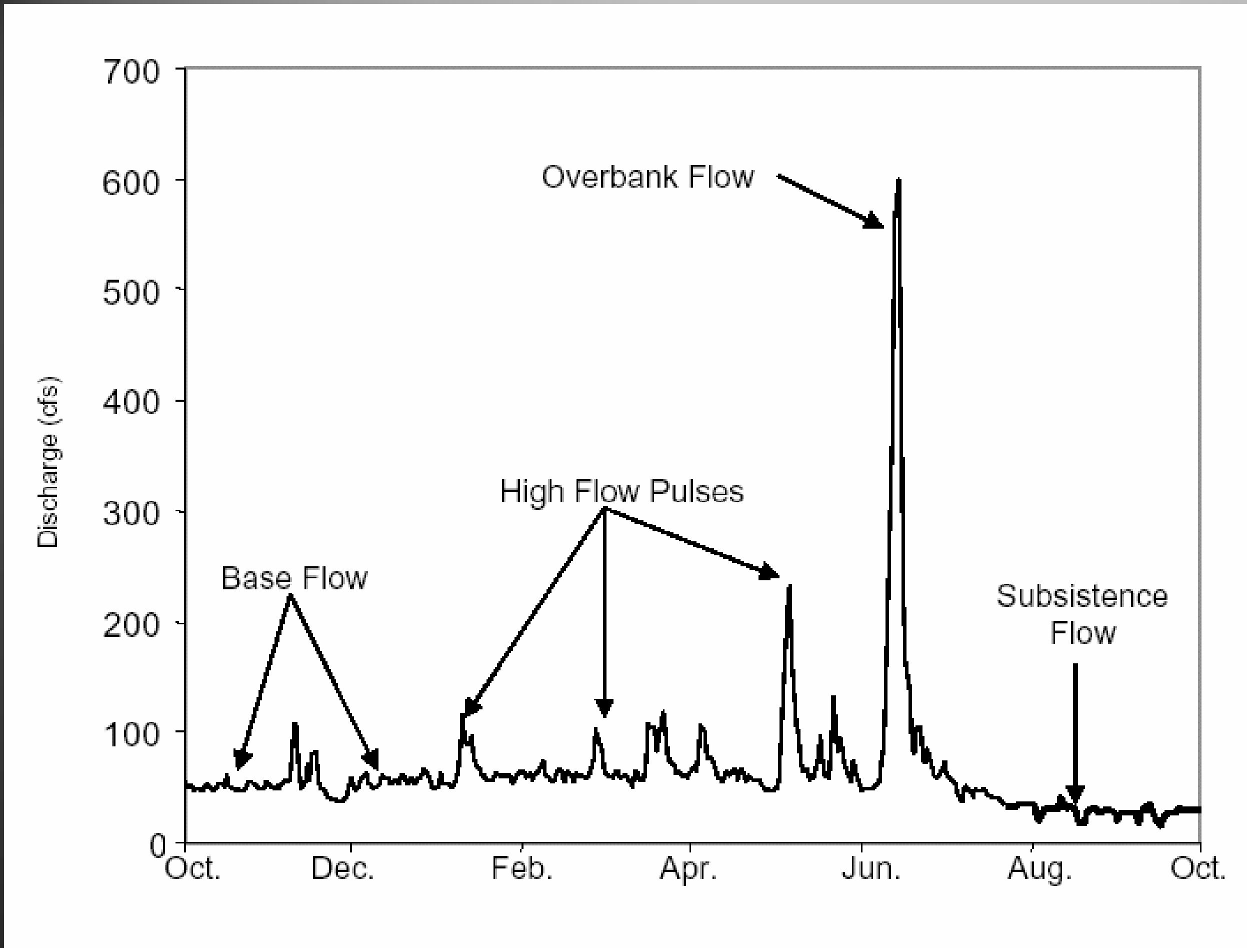


- Some flows have critical roles in habitat formation and maintenance
    - Overbank flows maintain floodplain features
    - Bankfull flows maintain bars, pool/riffle sequences
    - Moderate and high flows transport sediment delivered from upstream
- Flow variability matters because many species evolved to exploit a mosaic of habitats

National Research Council, 2005

" … instream flow programs need well-defined and measurable goals to frame instream flow studies and evaluate program progress."





National Research Council, 2005

The Science of Instream Flows: a review of the Texas instream flow program

"state-of-the-science programs use natural flow characteristics as a reference for determining flow needs. Natural river systems have variable flows (also called flow regimes) within a year and among multiple years … This natural variability is important to sustain aquatic and riparian biota and riverine processes."